Starburst Galaxy M82

Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA) , Apr 24, 2006

MAARSS

Magnet Architectures and Active Radiation Shielding Study with High Temperature Superconductors

NIAC Phase 2 Symposium

February 4, 2014

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Active Shielding – A New Approach

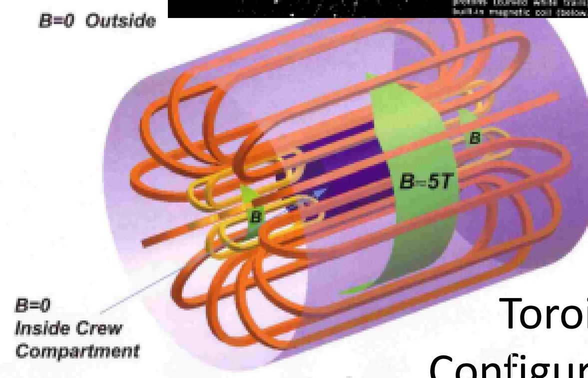
- Recent advances in superconducting magnet technology and manufacturing have opened the door for re-evaluating active shielding solutions as an alternative to mass prohibitive passive shielding

- Main Objectives
  - Analyze new coil configurations with maturing superconductor technology
  - Develop vehicle-level concept solutions and identify engineering challenges and risks
  - Shielding performance analysis

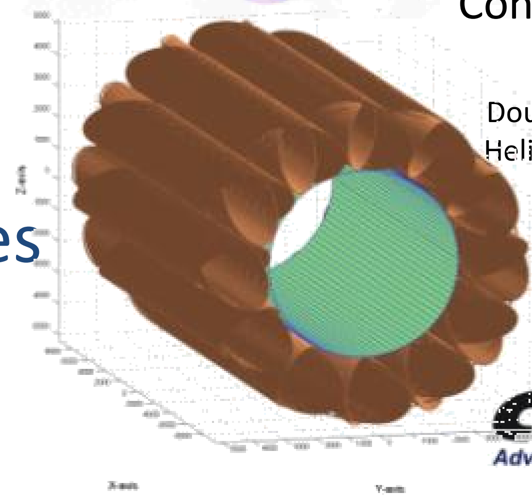
Phase 1 Report http://www.nasa.gov/directorates/spacetech/niac/westover_radiation_protection.html

A Foundation in Active Shielding

- Wernher von Braun, 1969
  - Mighty Magnets, Superconductivity
- J. C. Sussingham, 1999
  - Significant list of references
- L.W. Townsend, 2000
  - Active shielding summarized
- J.Hoffman, 2005
  - NIAC LTS toroid, AMS
- Battiston, 2011
  - ARSSEM, Double Helix Toroid
- Among many other studies



Toroid
Configuration



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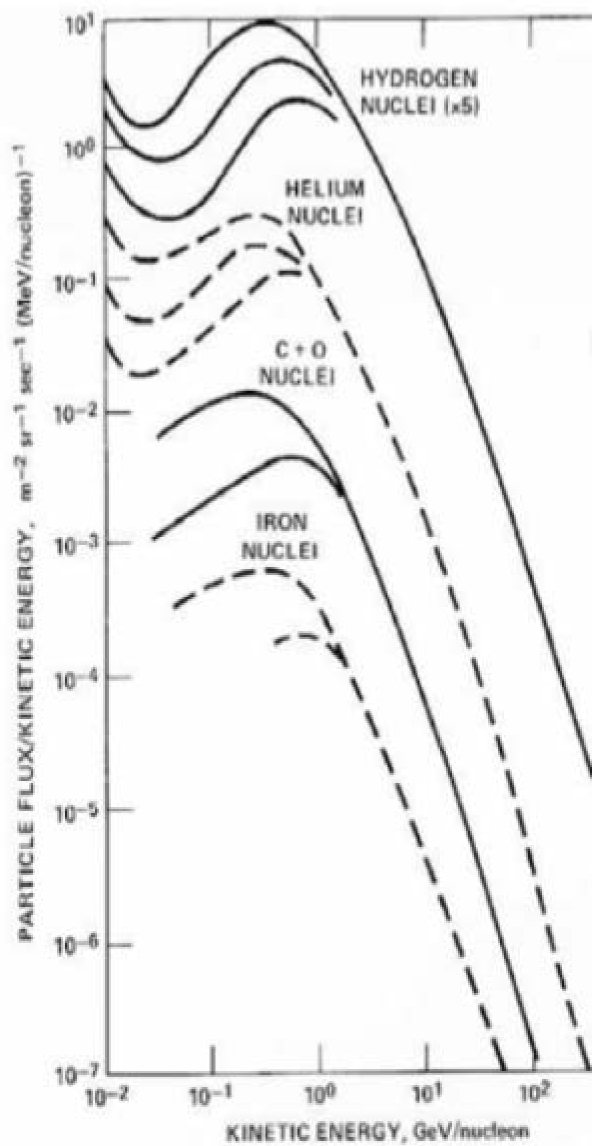
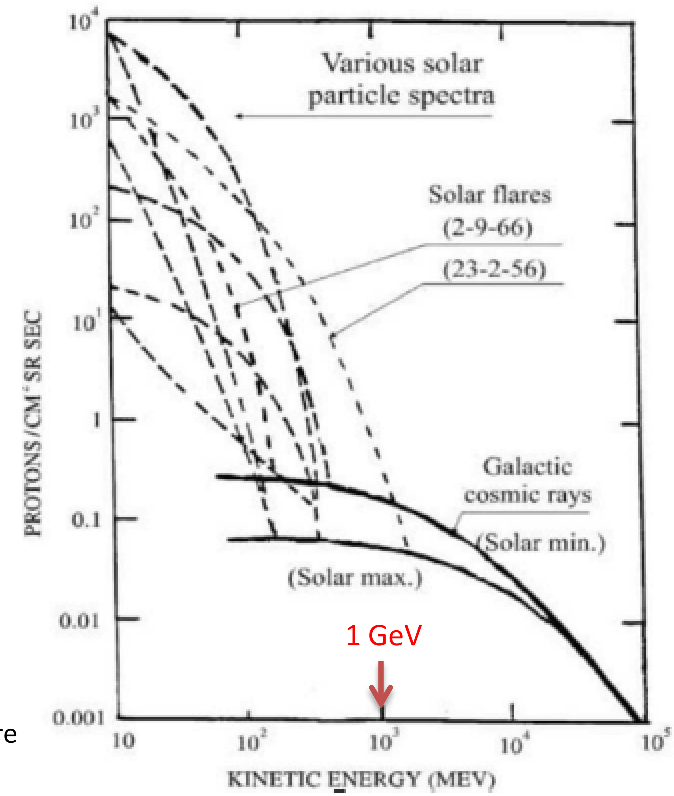
Radiation Environment



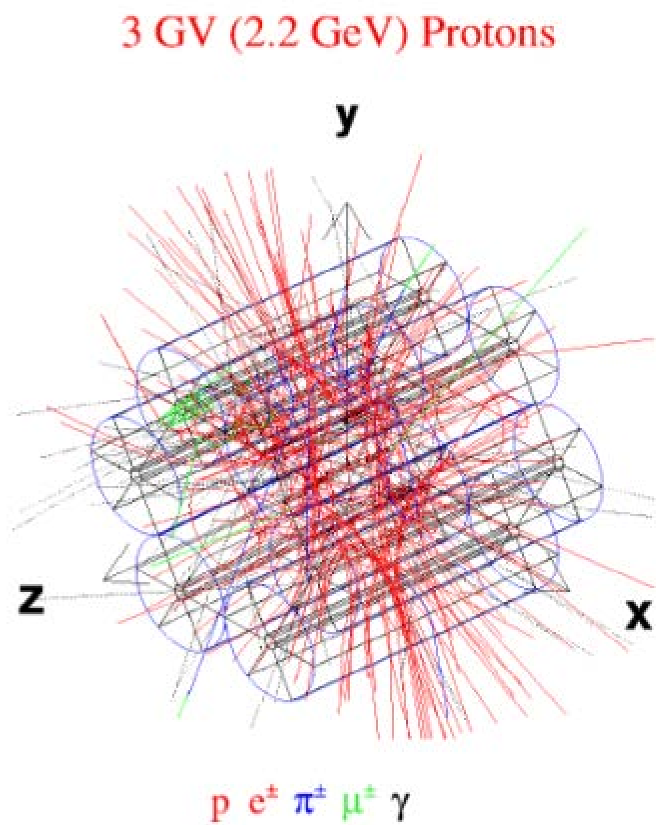
Common GCR species on the left graph.
Note the solar effects on the lower energy particles, hence the multiple curves per species. The GCR/SPE graph below shows the energy differences. *(Physics Today, Oct. 1974)*

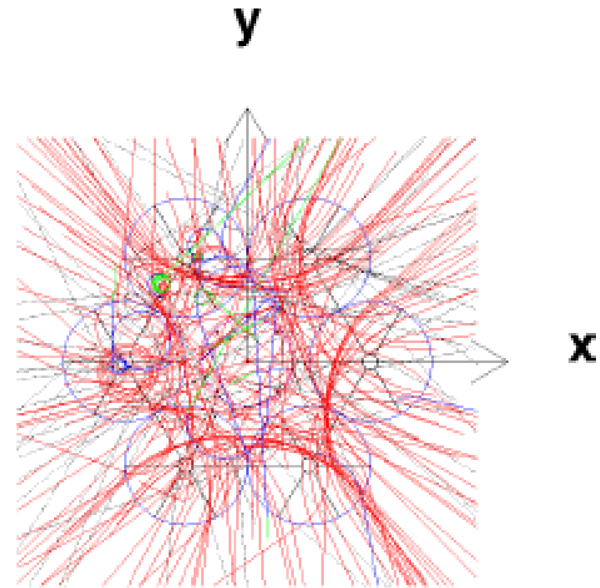
Graphic of Earth's Magnetosphere
Credit: THEMIS, nasa.gov



GCR: Galactic Cosmic Radiation
SPE: Solar Proton Event

Radiation Dose Monte Carlo Analysis



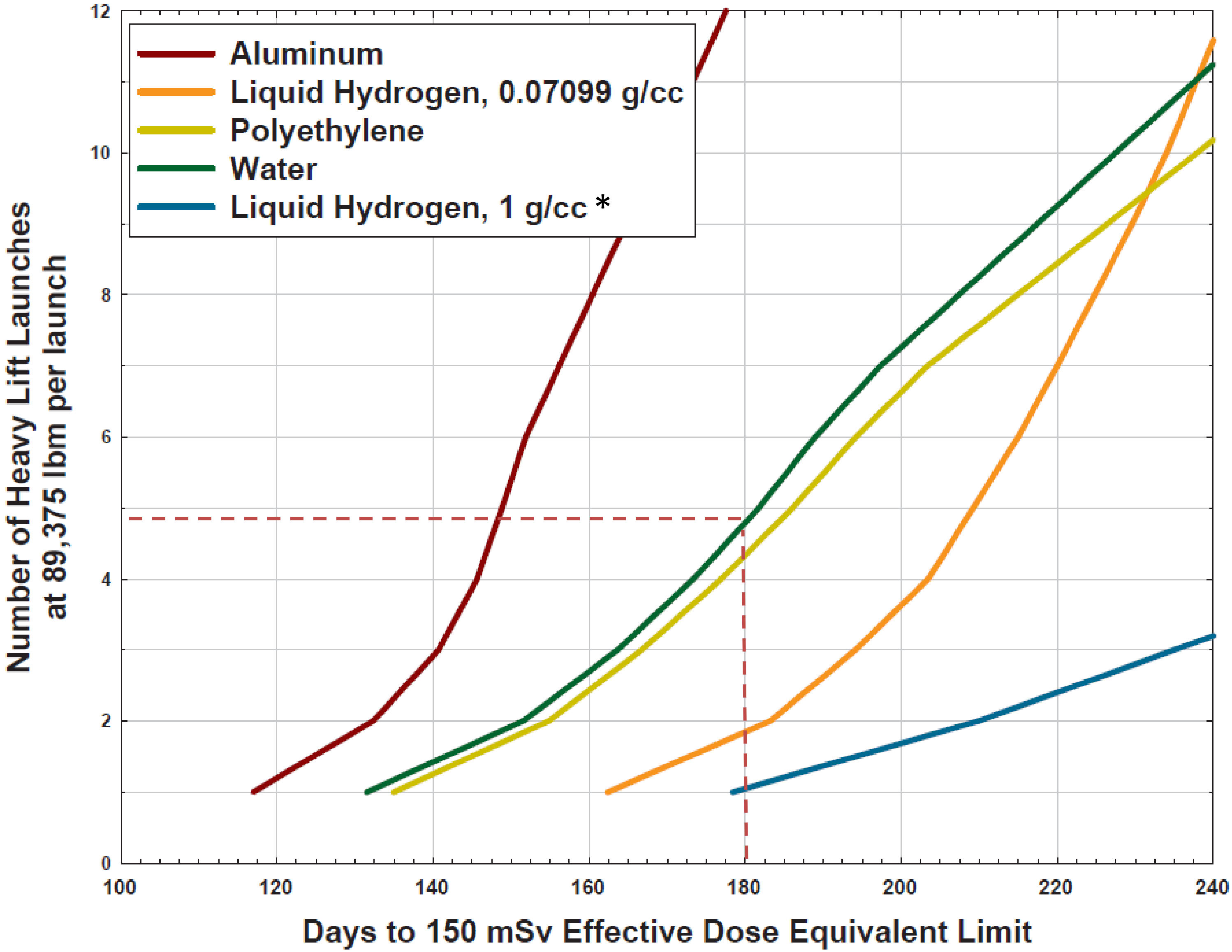


Secondary particles must be accounted for in dose evaluation

- Monte Carlo analysis includes millions of particle traces to evaluate total dose on a human sized volume within the habitat
- Graphics are a special generation meant to show, at a single proton energy, the effect of the magnet field

INFN, University of Perugia/W. Burger

Passive Shields



*Note the Liquid H2, 1 g/cc is fictional

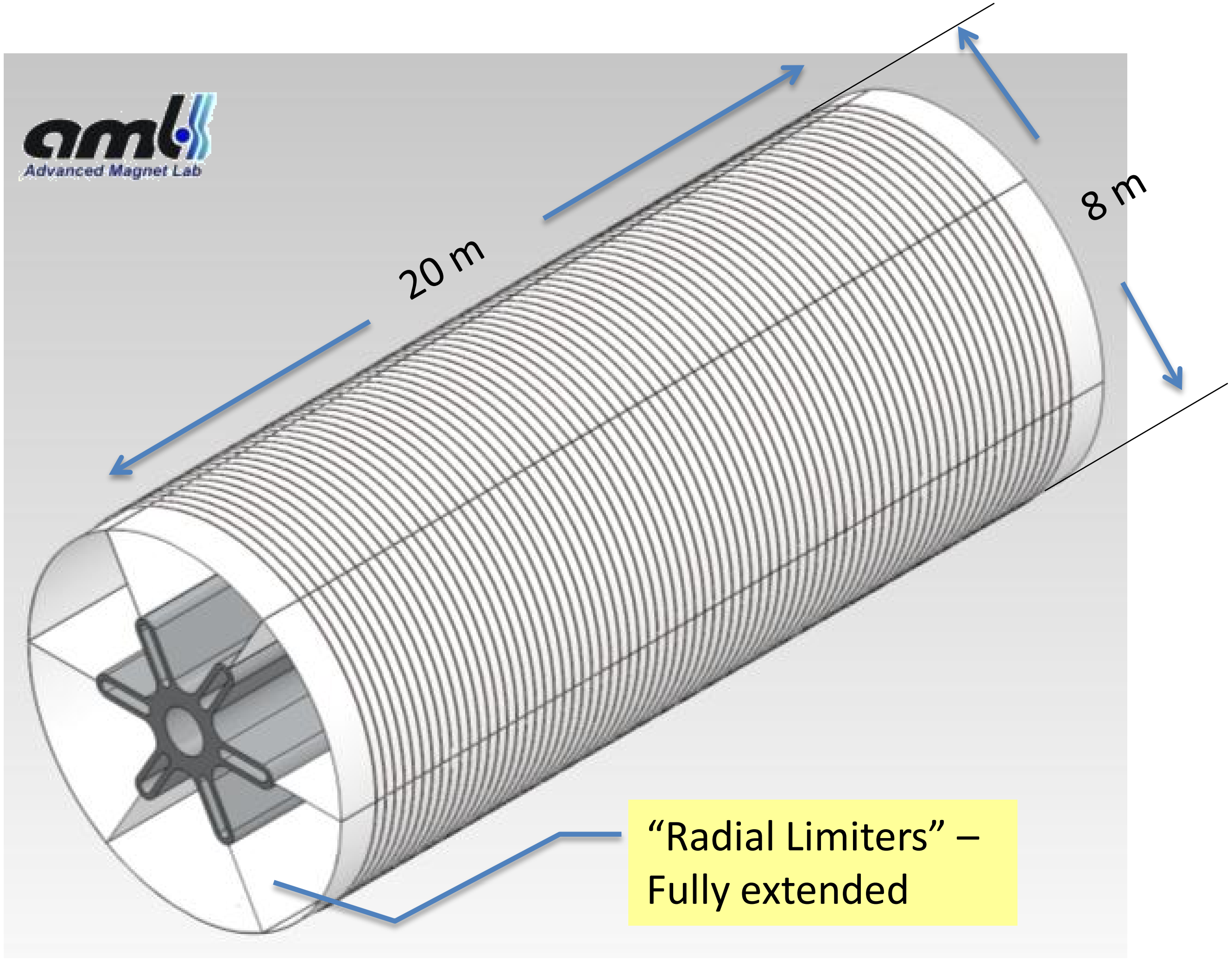
Per LaRC/R. Singletery

6+1 Configuration

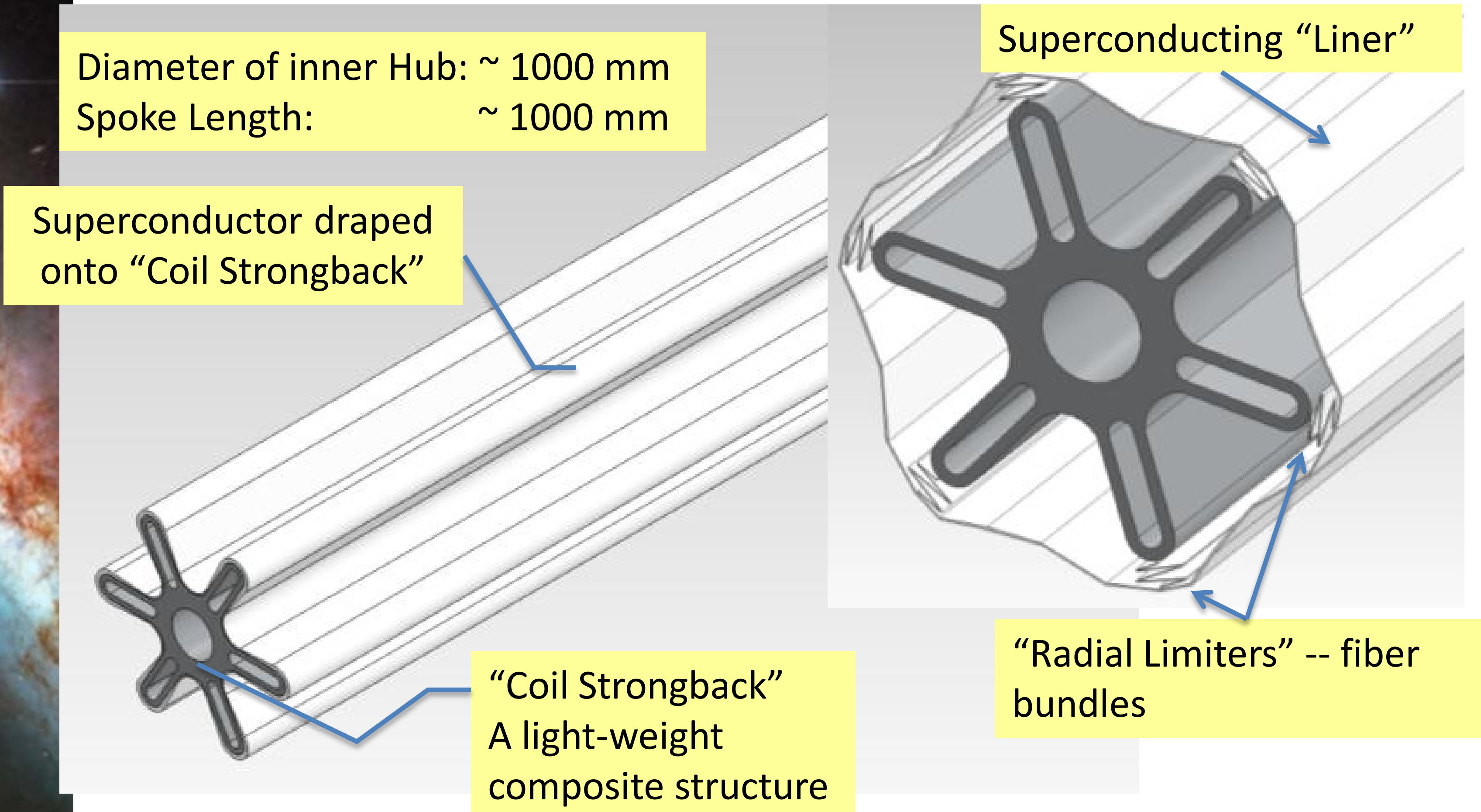
Parameter	Unit	Value
6 Solenoids Surrounding habitat		
Diameter	m	8.0
Length	m	15-20
Nominal Field	T	1.0
Nominal Current	kA	40
Stored Energy	MJ	400
Inductance	H	0.5
Magnetic Pressure	atm	~4

- Persistent mode operation
- Flux Pump charged
- Expandability considered

Large Fully Inflated Coil

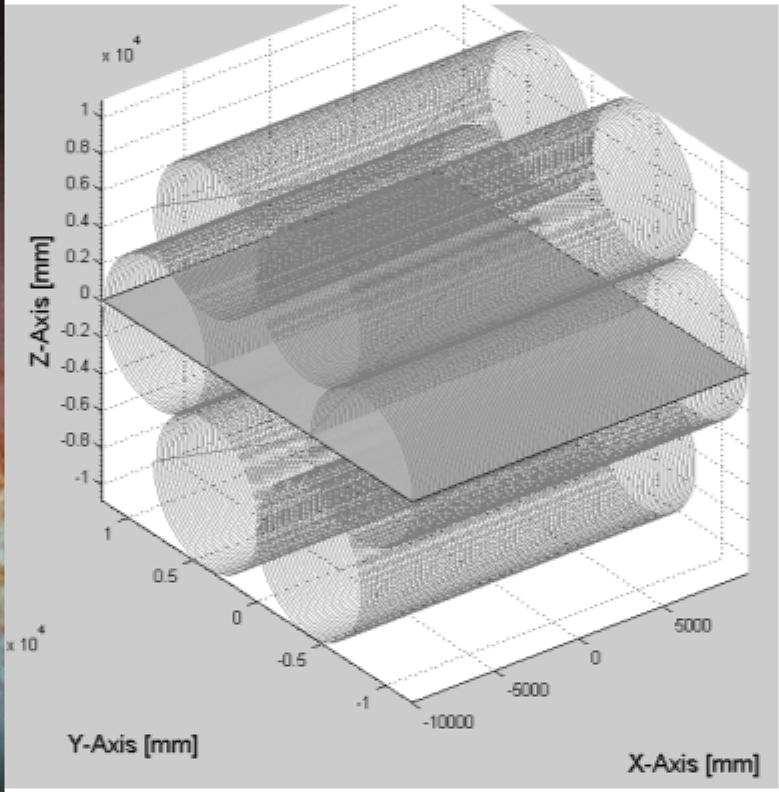


Solenoid Coil Fully Deflated then Partially Expanded

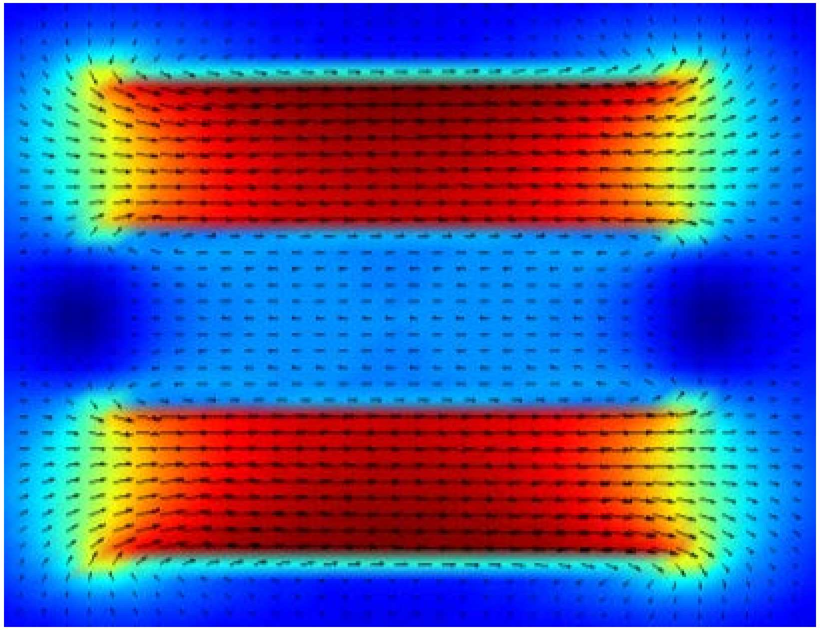


By vacuum pumping, the superconducting "Liner" is sucked to the "Strongback Coil" surface, closely following its contour of the "Spokes".

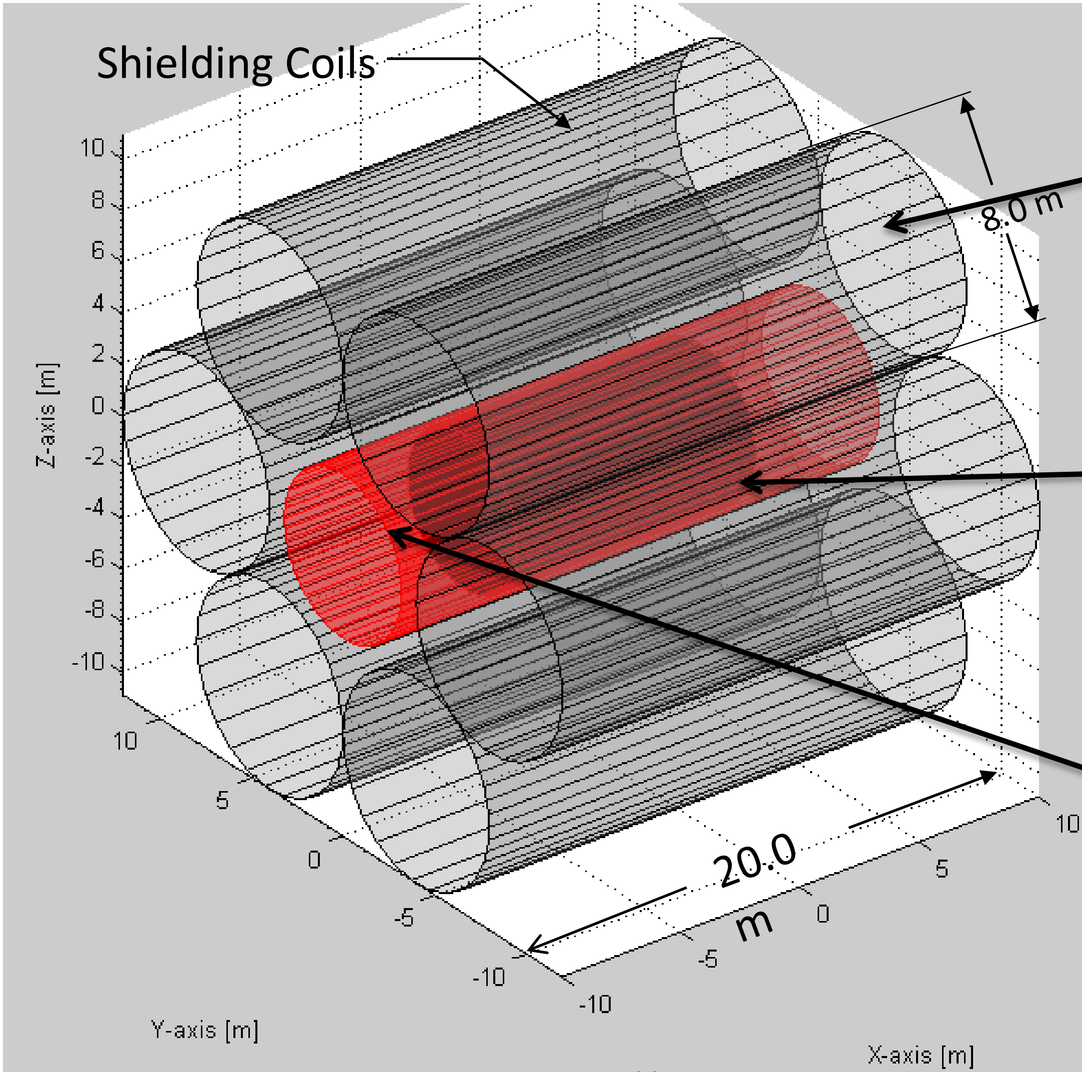
Analyze Field in Indicated X-Y-Plane



Field in X-Y-Plane



Shielding Coils with Habitat and Compensation Coil



6 shielding coils of 8 meter dia.

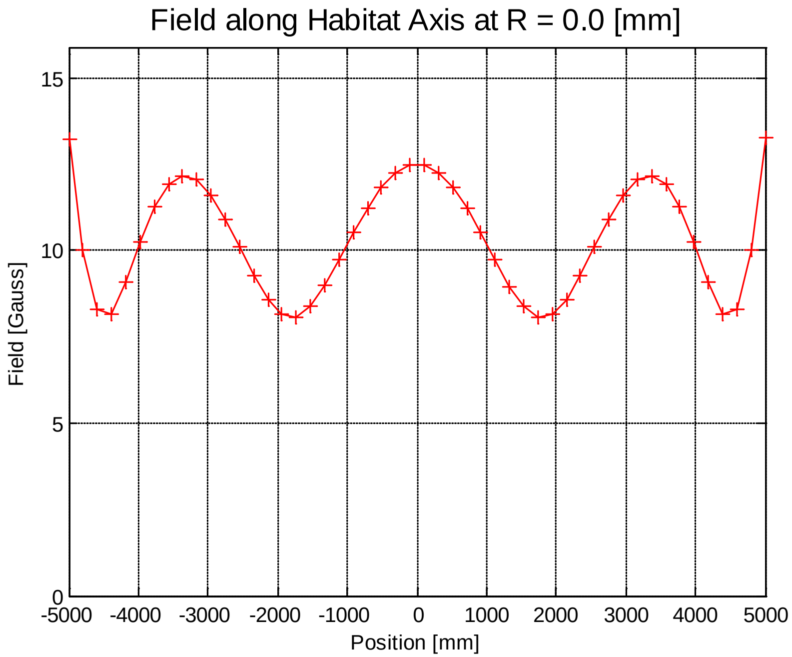
6 meter dia. Habitat

Compensation Coil

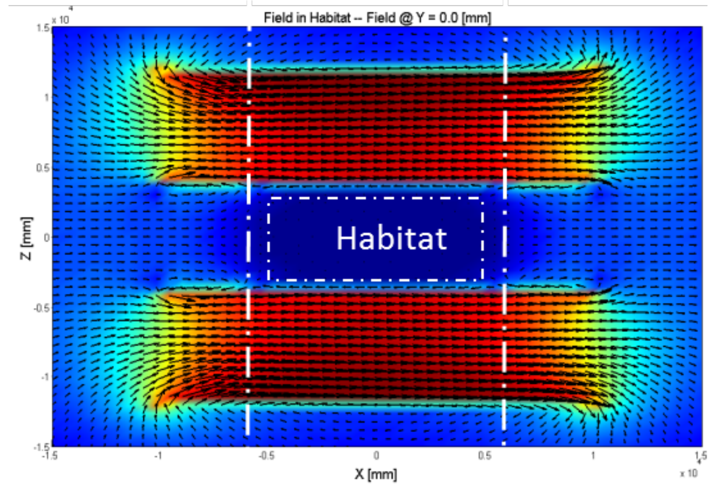
**Reduces magnetic field in habitat area from 2,500 Gauss to less than 20 Gauss

Rest Field with Modulated-Pitch Solenoid

Single Compensation Coil



Split Compensation coils reduce this field further



Pitch length decreases towards coil ends
Similar to MRI Gradient Coils

Diameter, *pitch length* and current of Compensation coil optimized:

Diameter of Compensation Coil	7.20 [m]
Length of Compensation Coil:	15.8 [m]
Current in Compensation Coil:	10220 [A]
Mean Field in Habitat:	**10.3 [Gauss]**

A Cycler Approach

- A deep space cycler is our approach for an active shield architecture
  - An active shield approach would need to be useable for multiple missions
    - Architecture cost
  - An active shield design is less complex when maintained in deep space
    - Simplify thermal management systems

- Launch, Assembly and Voyage (asteroid mission discussed here)
  - Heavy lift delivery of shielding coils to low earth orbit (LEO)
    - Deploy coil array in LEO, such as the Earth-Moon L2
  - Heavy lift delivery of compensation coil and habitat (LEO)
    - Dock with Shielding coil assembly in LEO
  - Delivery of mission support (food/water/propulsion/power)
    - Mission dependent – Need a Design Reference Mission study
    - Power deployment will enable coil charging and expansion
  - Deliver spacecraft to high earth orbit (HEO) such as the Earth-Moon L2
    - Using solar electric propulsion tug or chemical
  - Delivery of crew (Crew Module)
    - Field charging prior to and after crew arrival and dock?
  - Round trip to destination and return to HEO with CM/SM lifeboat
    - Crew Undock and return home in MPCV-like vehicle


Active Radiation Shielding
6 + 1 Expansion Coil Architecture
Two-Launch Assembly
Six-Coil Launch
Habitat & Compensator
Coil Launch
Orion
Spacecraft
Helium Vapor
Cooling System
Logistics Module
Habitat Module
Exploration
Propulsion Module
Habitat View
NIAC

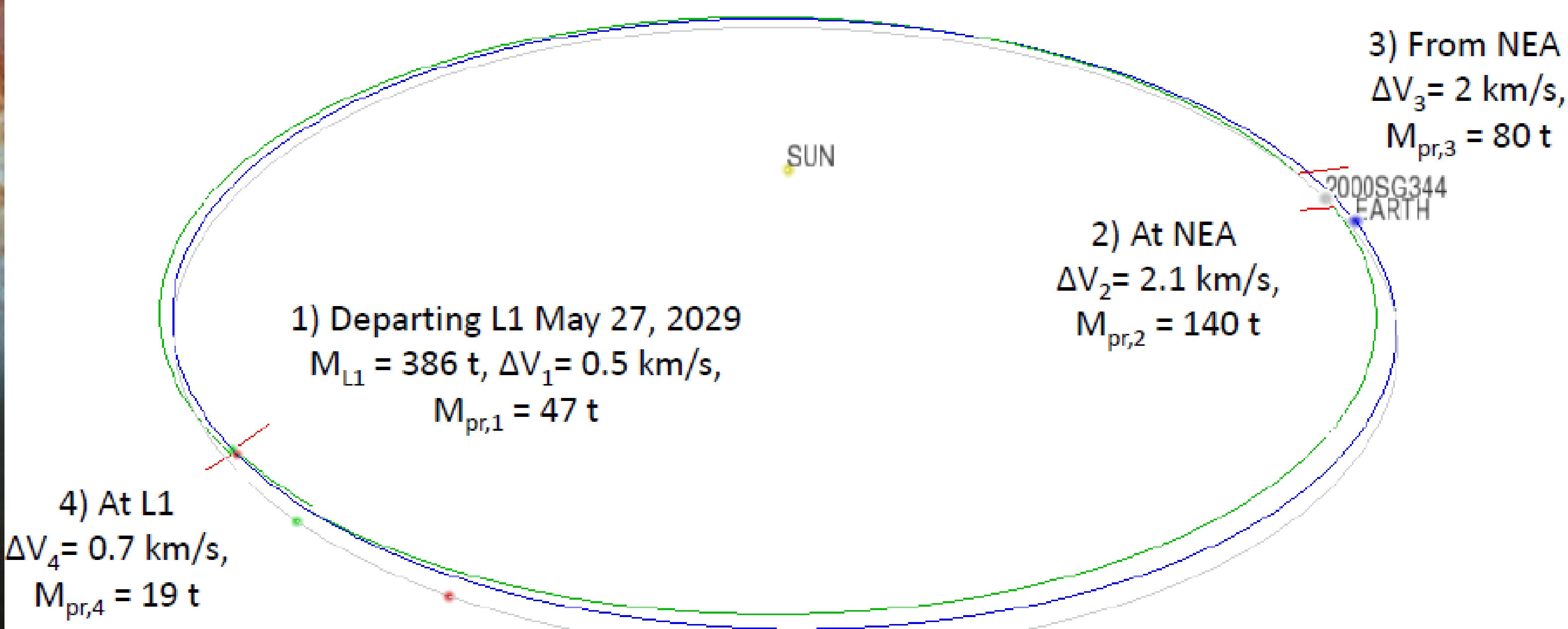
Propulsion Shielding Potential

- Two in-space propulsion architectures selected to envelope passive shielding potential
  - Chemical (LOX/LH2): selected for significant mass; in space storage remains an issue but it was used to evaluate the significant hydrogen content for shielding
  - Very High Power Solar Electric Propulsion (SEP): selected for minimal mass (less shielding potential).

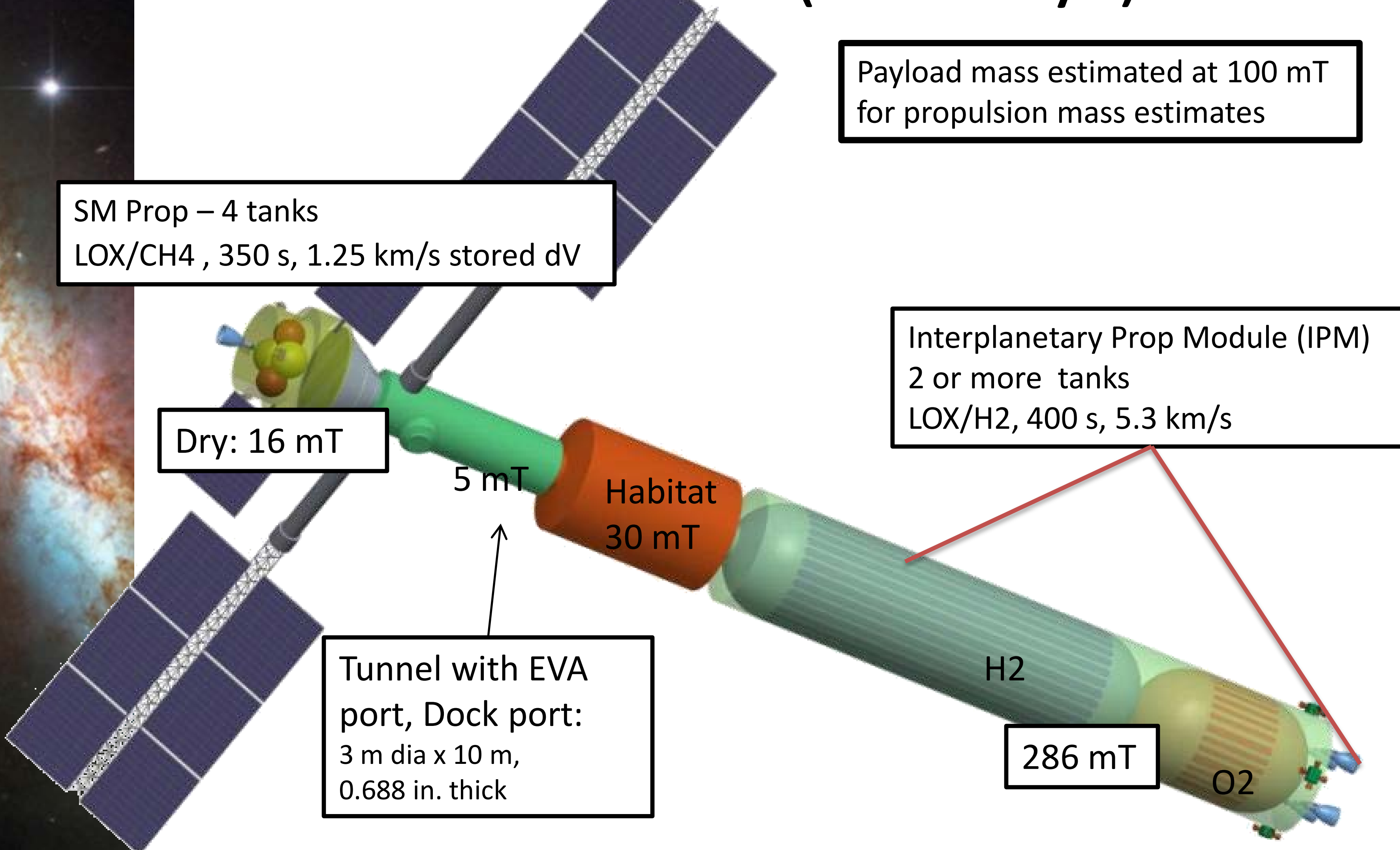
L1 – NEA Roundtrip Chemical Mission

Input:
$M_{PL} = 100$ t, $T < 1$ year
$I_{sp} = 400$ sec (LOX+LH2)

Output:
$M_{prop} = 286$ t , $M_{L1} = 386$ t
$\Delta v_{total} = 5.3$ km/s



NEA – Chemical (365 days)



Comp coil, 8 Tm coils (not shown): 53 mT (iteration 1)

Annual Skin, BFO and Whole Body Equivalent Doses* for Geometry 27 (NEA-C) at Solar Minimum

Iteration 1 (phase 1)

No End Cap Architecture
Not included: habitat mass, consumables, propellant, etc.

Z	Total			Barrel Region		
1	14.4	13.7	13.4	7.9	7.6	7.4
2	6.6	5.7	5.6	3.8	3.4	3.4
3-10	22.5	14.3	7.5	15.4	10.8	5.2
11-20	18.4	8.8	7.1	12.7	6.9	5.2
21-28	8.1	2.6	2.7	5.7	2.2	2.0
Total	70.0	45.1	36.3	45.5	30.9	23.2
fraction of total dose:				0.65	0.69	0.64

Limit approximately corresponds to 15 cSv *under conservative assumptions*

cSv/rem

The Barrel Region corresponds to the acceptance covered by the magnetic shield.

*Average values of the six water cylindre positions

Annual Skin, BFO and Whole Body Equivalent Doses* for Geometry 27 (NEA-C) at Solar Minimum

Iteration 1

No End Cap Architecture
Not included: habitat mass, consumables, propellant, etc.

Z	Total			Barrel Region		
1	14.4	13.7	13.4	7.9	7.6	7.4
2	6.6	5.7	5.6	3.8	3.4	3.4
3-10	22.5	14.3	7.5	15.4	10.8	5.2
11-20	18.4	8.8	7.1	12.7	6.9	5.2
21-28	8.1	2.6	2.7	5.7	2.2	2.0
Total	70.0	45.1	36.3	45.5	30.9	23.2

fraction of total dose: 0.65 0.69 0.64

Iteration 2

End Cap Architecture
Includes chemical LOX/LH2, MPCV, tunnel

Z	Total			Barrel Region		
1	15.4	14.6	14.2	9.5	9.1	8.8
2	6.7	5.9	5.7	4.4	4.1	3.8
3-10	21.0	14.0	7.2	15.5	11.1	5.4
11-20	16.3	8.1	6.7	11.9	6.4	5.3
21-28	6.9	2.3	2.5	5.7	1.9	2.1
Total	66.3	44.9	36.3	47.0	32.6	25.4

cSv/rem

fraction of total dose: 0.71 0.73 0.70

The Barrel Region corresponds to the acceptance covered by the magnetic shield.

*Average values of the six water cylindre positions

Limit approximately corresponds to 15 cSv *under conservative assumptions*

Annual Skin, BFO and Whole Body Equivalent Doses* for Geometry 27 (NEA-C) at Solar Minimum

Iteration 1

No End Cap Architecture
Not included: habitat mass, consumables, propellant, etc.

Z	Total			Barrel Region		
1	14.4	13.7	13.4	7.9	7.6	7.4
2	6.6	5.7	5.6	3.8	3.4	3.4
3-10	22.5	14.3	7.5	15.4	10.8	5.2
11-20	18.4	8.8	7.1	12.7	6.9	5.2
21-28	8.1	2.6	2.7	5.7	2.2	2.0
Total	70.0	45.1	36.3	45.5	30.9	23.2

fraction of total dose: 0.65 0.69 0.64

Iteration 2

End Cap Architecture
Includes chemical LOX/LH2, MPCV, tunnel

Z	Total			Barrel Region		
1	15.4	14.6	14.2	9.5	9.1	8.8
2	6.7	5.9	5.7	4.4	4.1	3.8
3-10	21.0	14.0	7.2	15.5	11.1	5.4
11-20	16.3	8.1	6.7	11.9	6.4	5.3
21-28	6.9	2.3	2.5	5.7	1.9	2.1
Total	66.3	44.9	36.3	47.0	32.6	25.4

fraction of total dose: 0.71 0.73 0.70

cSv/rem

Iteration 3

In work: add habitat mass

The Barrel Region corresponds to the acceptance covered by the magnetic shield.

*Average values of the six water cylindre positions

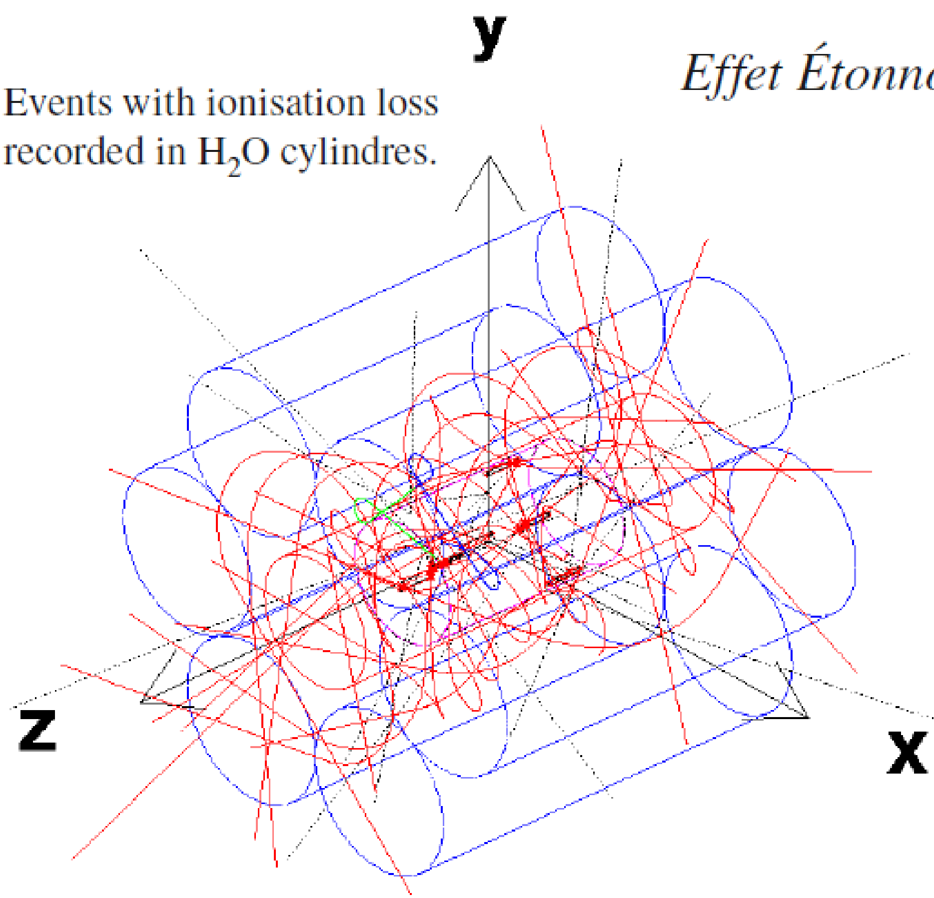
Limit approximately corresponds to 15 cSv *under conservative assumptions*

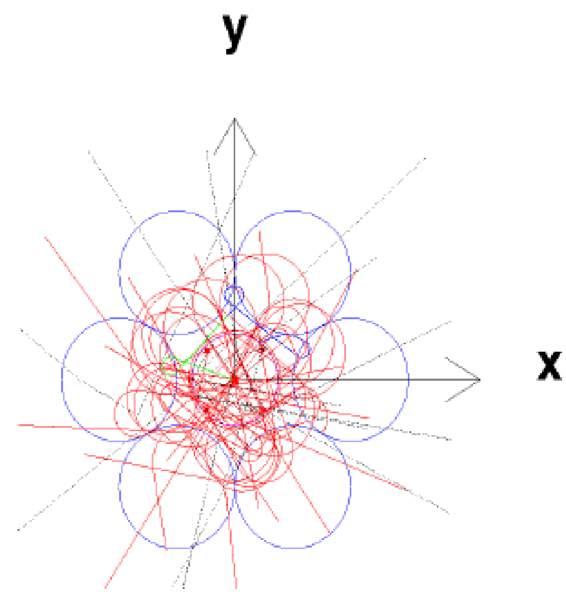
6+1 Expandable Solenoid Shield

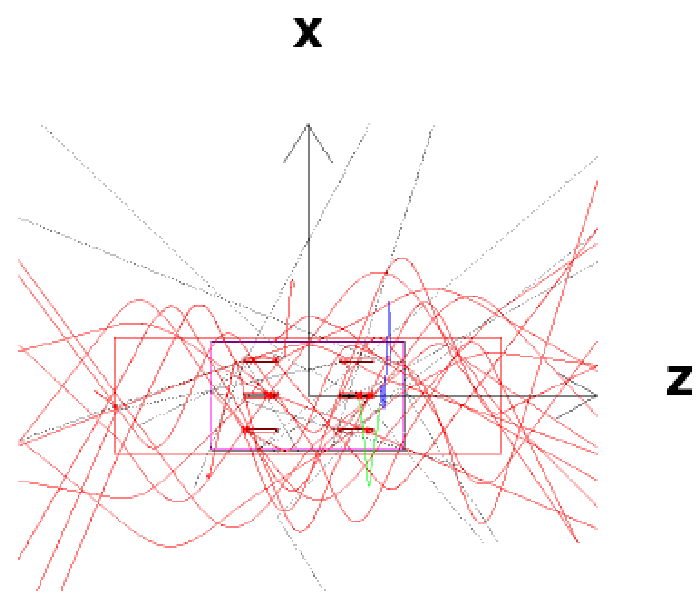
1 GV (0.43 GeV) Protons

Effet Étonnoir

Events with ionisation loss recorded in H_2O cylindres.

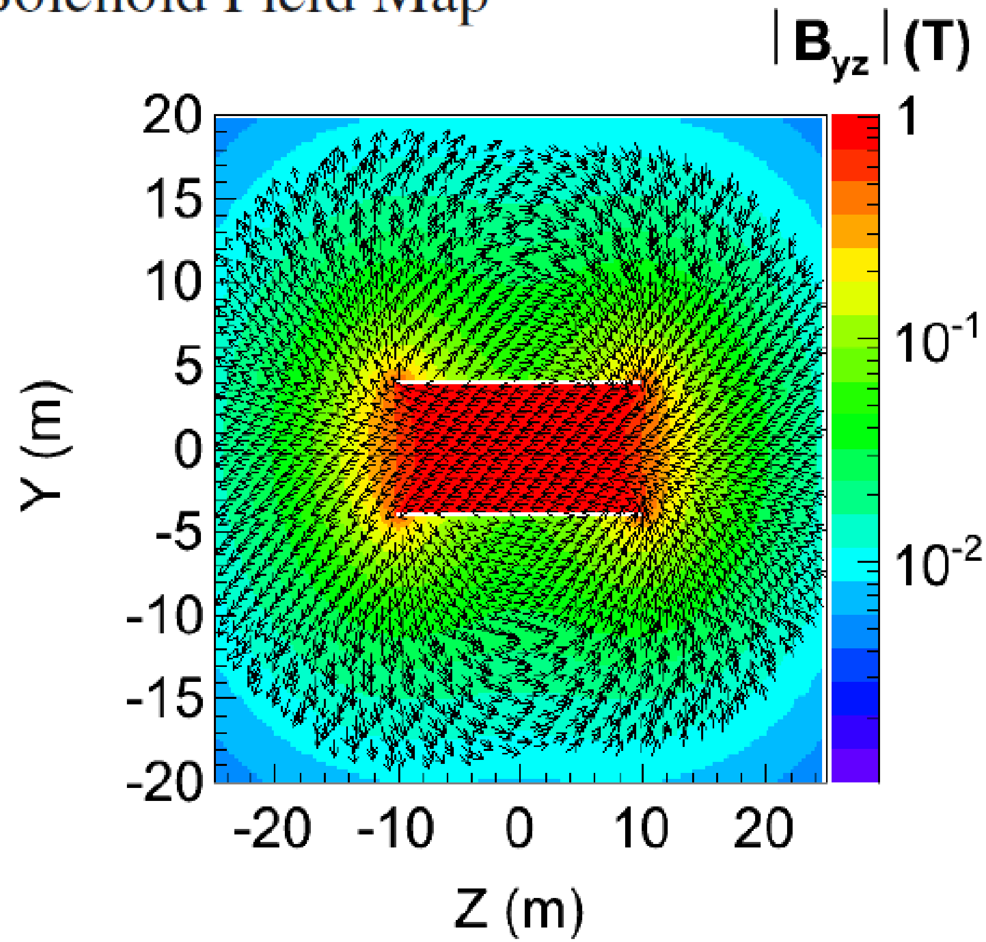






3000 protons generated uniformly across the two surfaces in the **xy** plane used to define the acceptance.

Shield Solenoid Field Map



Field computed at 5.9 M points uniformly spaced in a $40 \times 40 \times 50\ \ m^3$ volume using the Biot-Savart law, with 400 current loops along the 20 m solenoid cylindre, and 180 current elements in each loop.

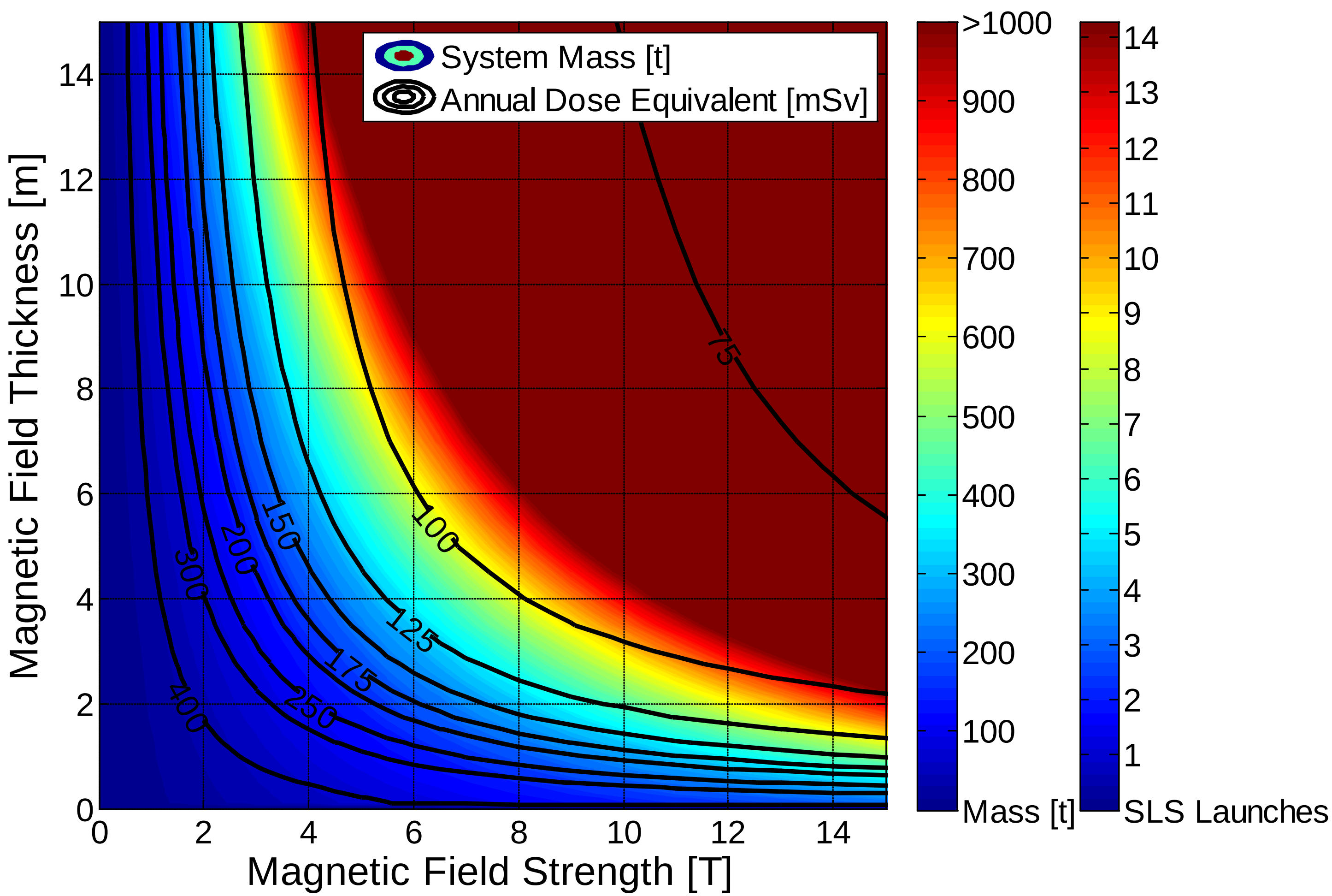
Model & HZETRN

- An analytical-HZETRN model was developed to allow the rapid analysis of a broad range of trade space variables for a solenoid shaped, active magnetic shield design
- This model assumes a single solenoid around the spacecraft for simplicity and provides a shielding performance analysis (mass and dose equivalent) of the 6-around-1 coil design
  - Mass assumes commercial off the shelf materials

HZETRN = High Charge and Energy Transport

Advanced Magnet Lab

Model & HZETRN



Summary of Key Parameters

Parameter	8 T m	20 T m	20 T m	25 T m
Flux Density	1.0 T	2.5 T	1.0 T	1.5 T
Diameter	8.0 m	8.0 m	20 m	16.7 m
Length	20 m	20 m	30 m	25 m
Volume	1,053 m^3	1,053 m^3	9,425 m^3	5,475 m^3
Current	43.5 kA	108.8 kA	50.0 kA	50 kA
Stored Energy	410 M Joule	2,520 M Joule	4580 M Joule	2670 M Joule
Inductance	0.43 Henry	1.1 Henry	3.7 Henry	2.1 Henry
Number of Turns	400	400/1000*)	600	500
Magnetic Pressure**)	4 atm	25 atm	4 atm	9 atm

*) Depending on Conductor Performance

**) $P_m = B^2/(2\mu_o)$

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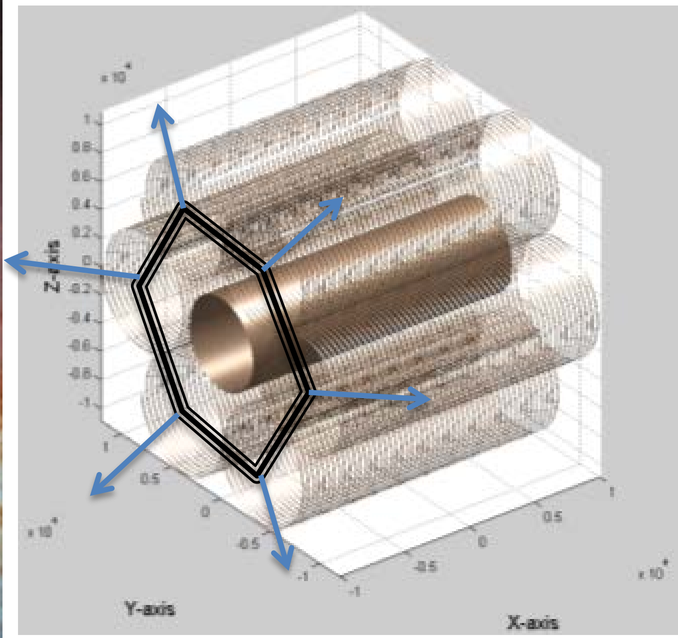
Loads and Structural Response

Forces Acting on Shielding Coil



Coils behave like 6 permanent magnets with strong repulsive forces

Inter-coil support structure needed

Forces act on conductors that are bonded to flexible fabric liner

Forces not uniform over length of solenoids

Possible bending on strong back

Distortion of ‘ideal’ cylinder geometry of each individual coil

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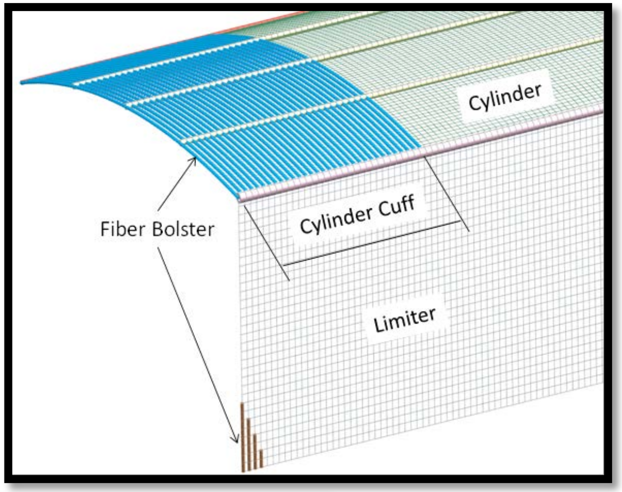
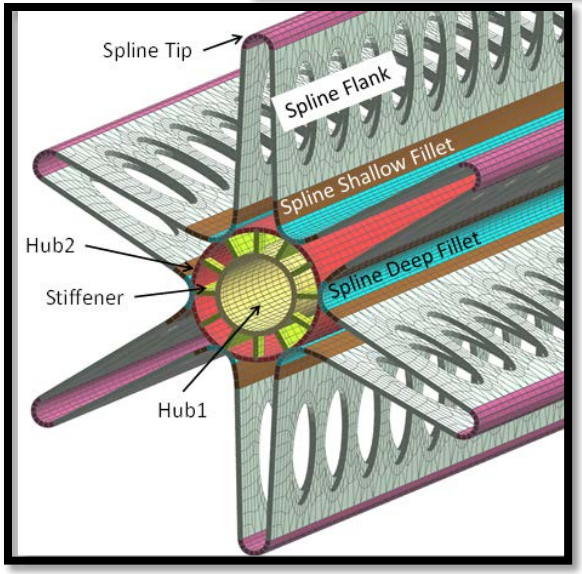
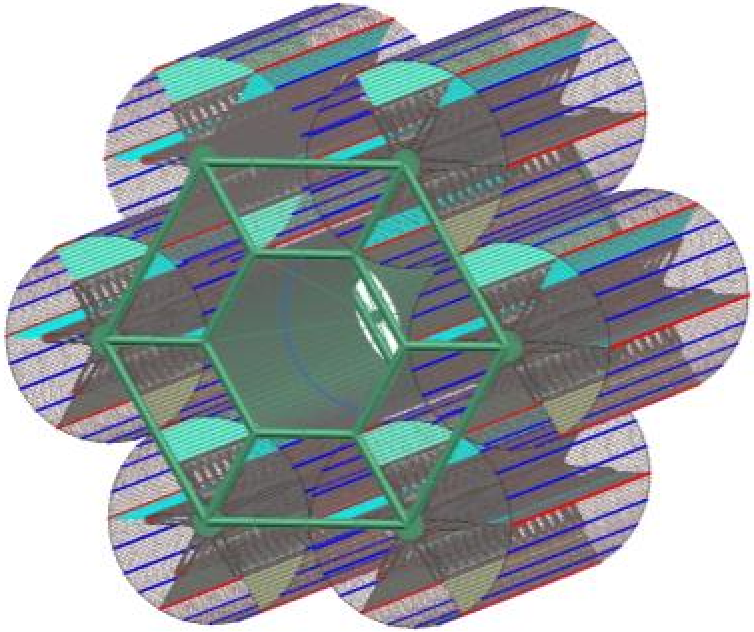
Baseline Structural Design:

- Primary differentiation between single and multi coil simulations are: mesh density, loads definition and coil connectivity structure (Yoke)

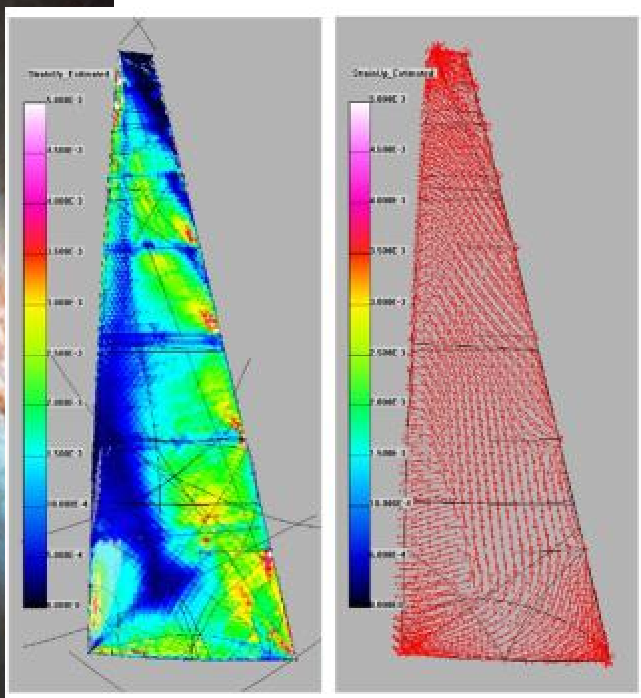






Bolstering: Flexible Laminate Reinforcement

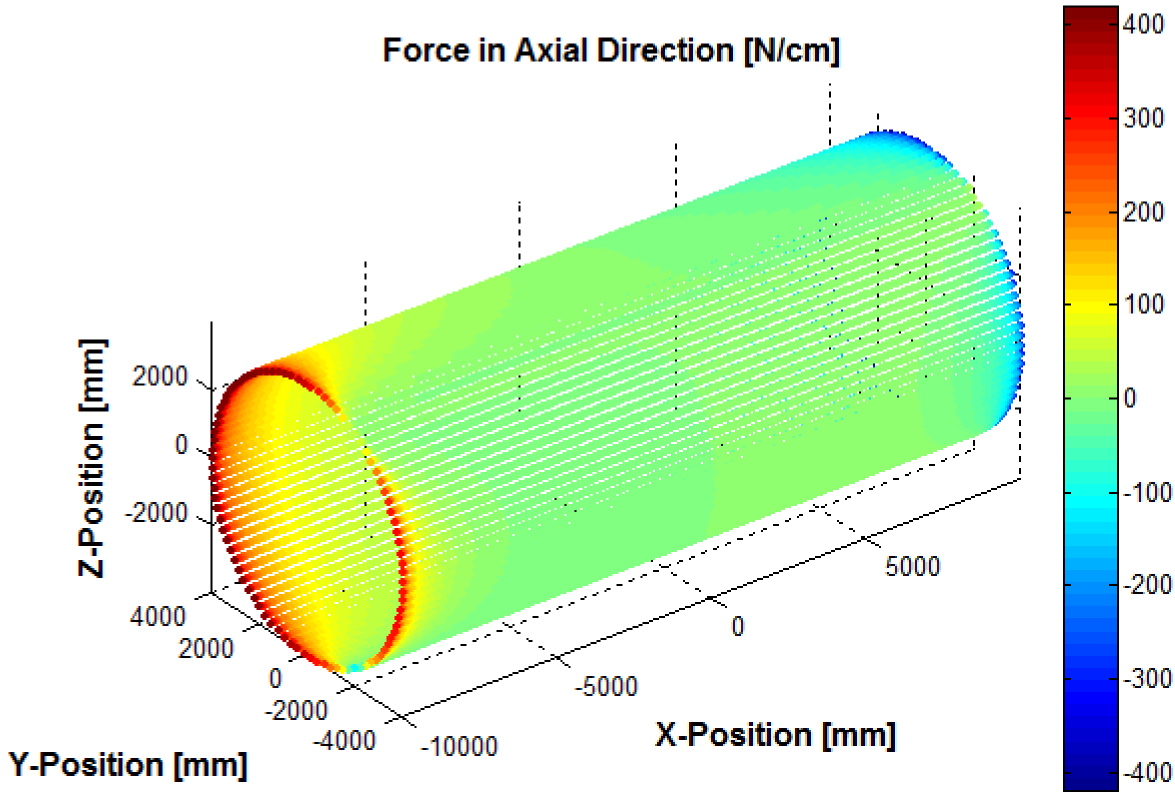
- Bolstering based on strain mapping (sail boat sails analogy)



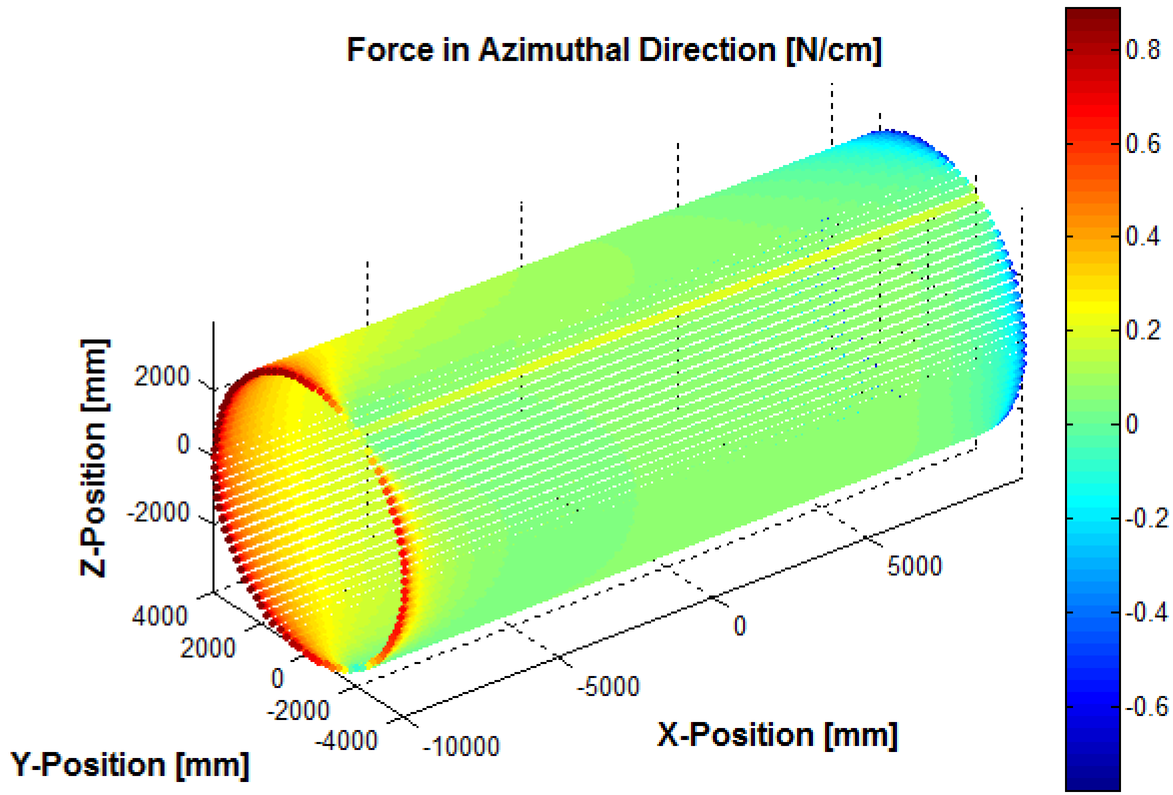
Membrane Loads and Deformations
(Strain mapping)

Bolster Design and Fabrication
(targeted fiber tow reinforcement)

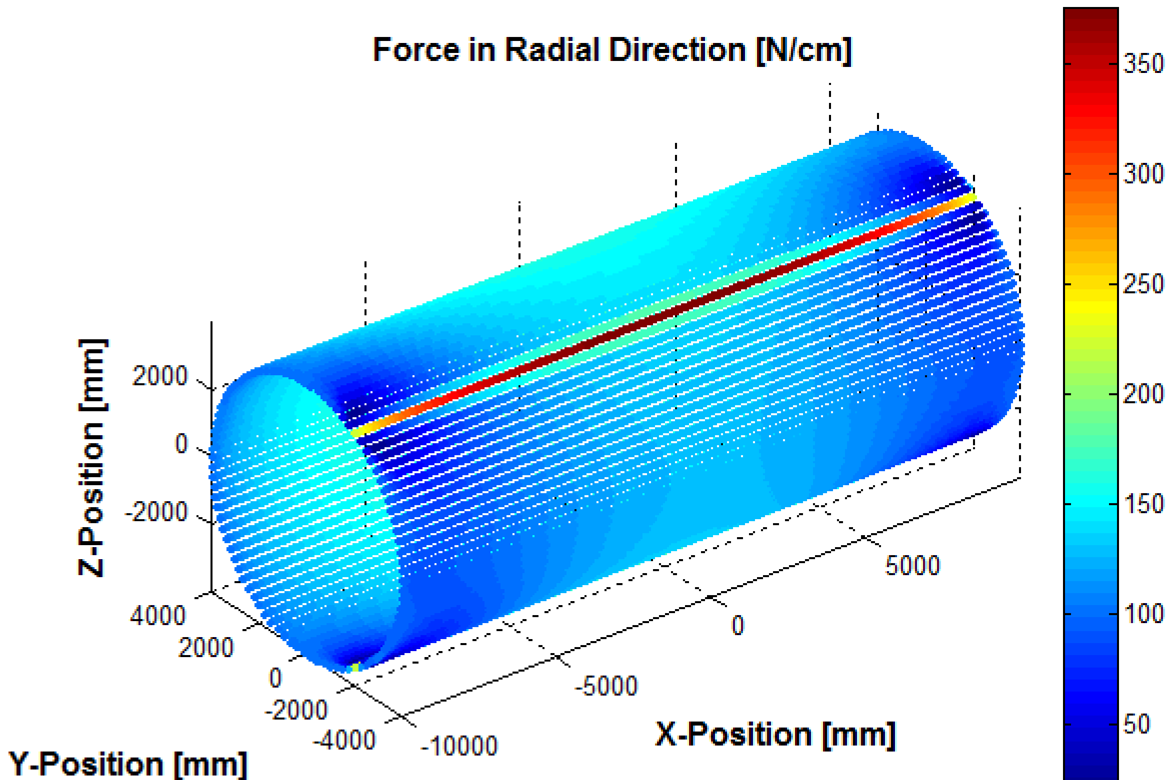
Axial Forces on Undistorted Array Solenoid



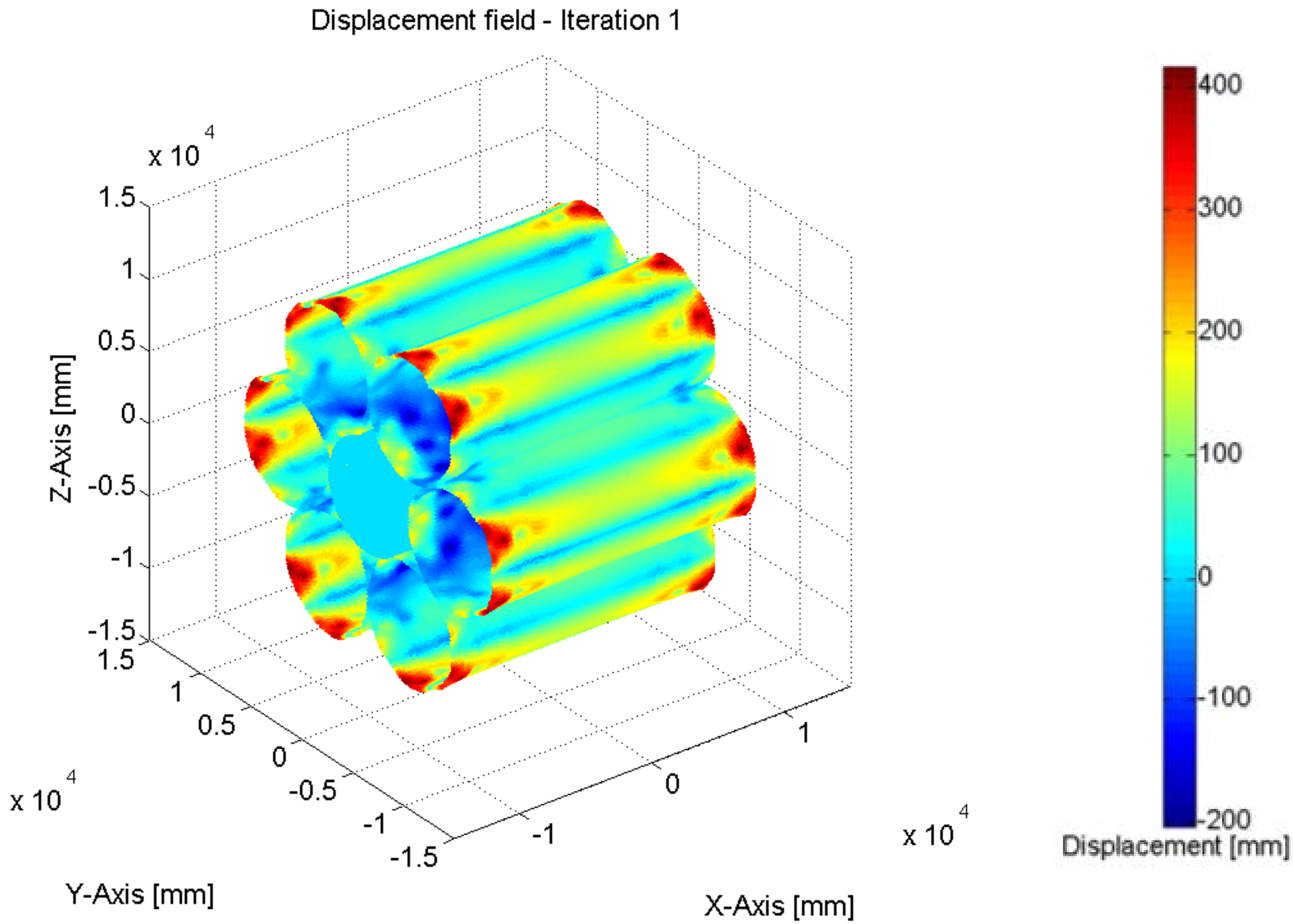
Azimuthal Forces on Undistorted Array Solenoid



Radial Forces on Undistorted Array Solenoid



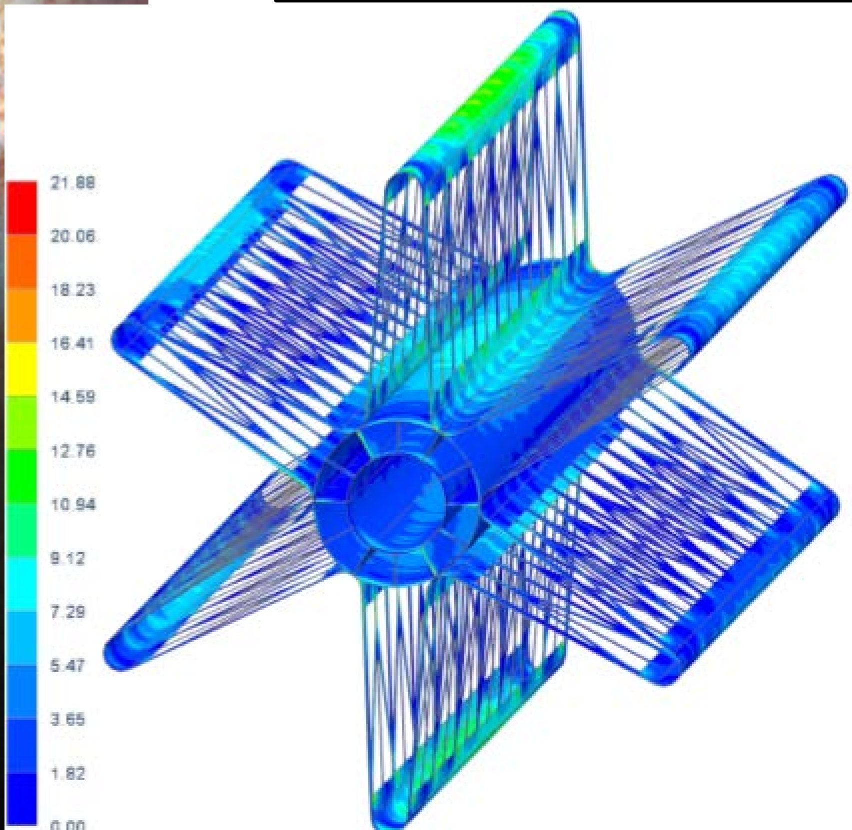
Induced Deformation in Shielding Array



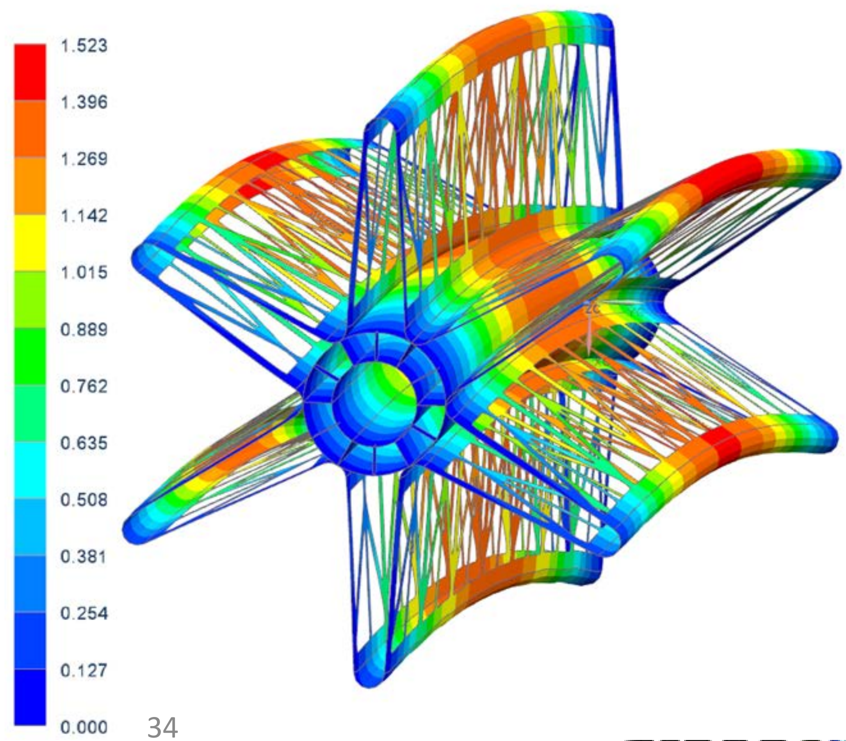
Structural Modeling: Coil Alone – Rigid Laminate

- Models 1 & 2 (model 2 shown):
  - von Mises Stress Comparison: Maximum Model 2 stress is 39.9% less than Model 1. Highest stress in fillet, far from imposed loads @ spline tip. Compliant structure spreads load.

Model 2 vs. Model 1: lighter, not as stiff and maximum operational σ may be lower. How does added displacement affect the field?

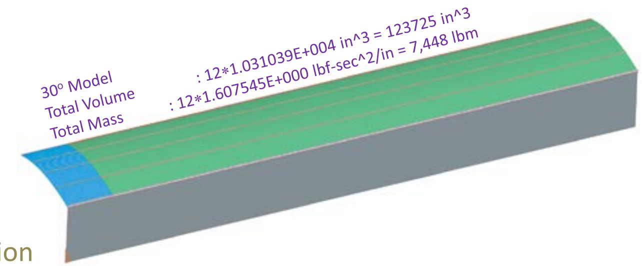


Displacement scale: 4x



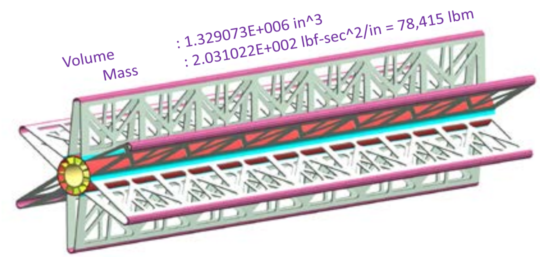
Summary: Weight Performance As Analyzed

- Performance relative to current technology readiness level (TRL) 6-7
  - Rigid and flexible composite structures perform well with regards to strength requirements
  - Estimated mass



- **Cylinder – 7,448 lbm**

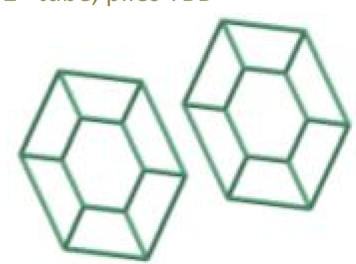
  Fiber *Material:* TorayCA T1000G
  Construction: 2 plies @ ±45^{o} orientation
  Cylinder: ¼” diameter tows
  Limiter: 0.354” diameter tows
  Local Bolster: ½” diameter tows
  Matrix: HexPly 954-6 cyanate epoxy resin.
  Film: DuPont Kapton E.



- **Strongback – 78,415 lbm**

  Fiber *Material:* Strongback: TorayCA M55J
  Spar and Batten: TorayCA T100G
  Construction: 0 ^{o}/90 ^{o} orientation
  Strongback: fiber, 32 plies @ Spars: fiber, 2”x1/2” tube, plies TBD
  Battens: 1” diameter rod , plies TBD
  Matrix: HexPly 954-6 cyanate epoxy resin.

- **Yoke – 2,608 lbm**



- **Total – 88,471 lbm**

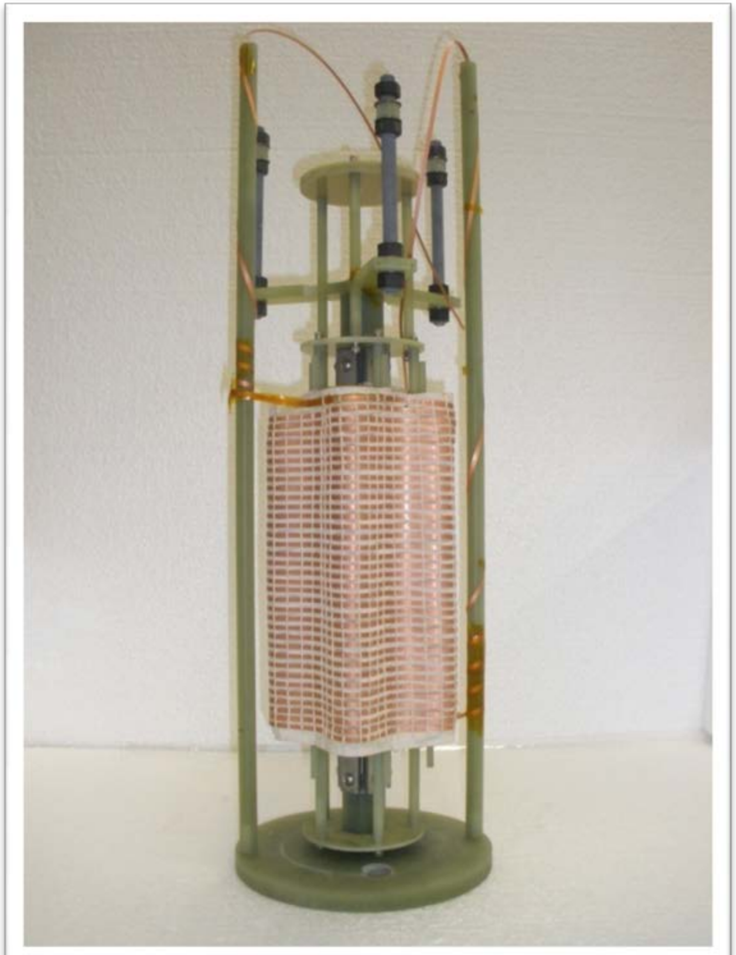
Mass Summary

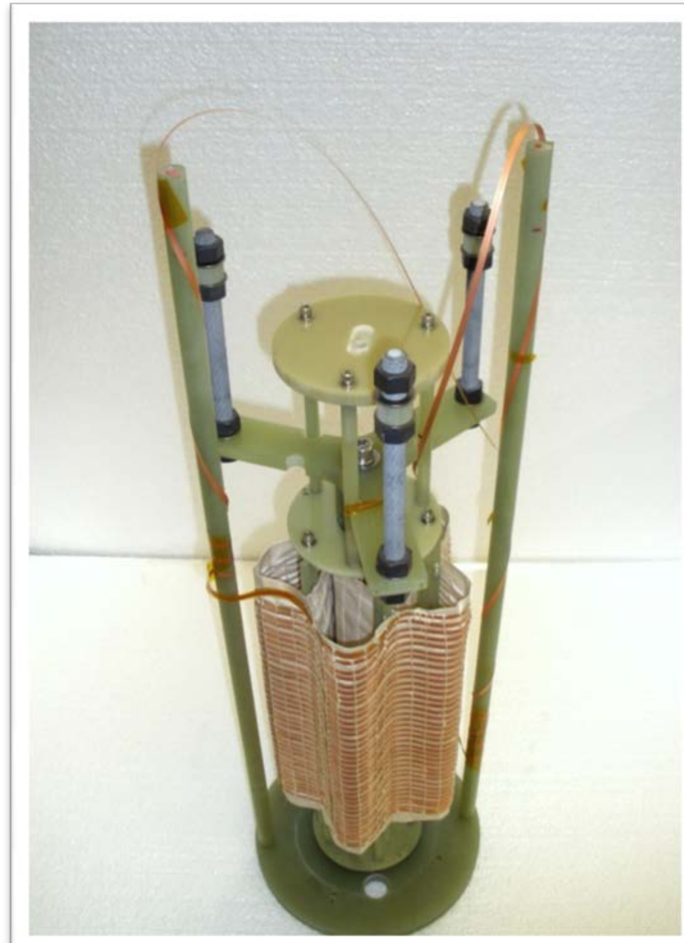
- Strong-back mass needs work
  - Current design utilizes today's available materials and is a foundation to future iterations on design and incorporation of advanced materials
- Minimize launch mass and assembly complexity
  - Block 2 SLS: desire single launch of 6 coils to LEO
  - Recent analysis suggests SLS Block 2 delivery of 3 coils to LEO with current off the shelf composites

SLS = Space Launch System

Testing

Expandable Coil – Collapsed (AML)



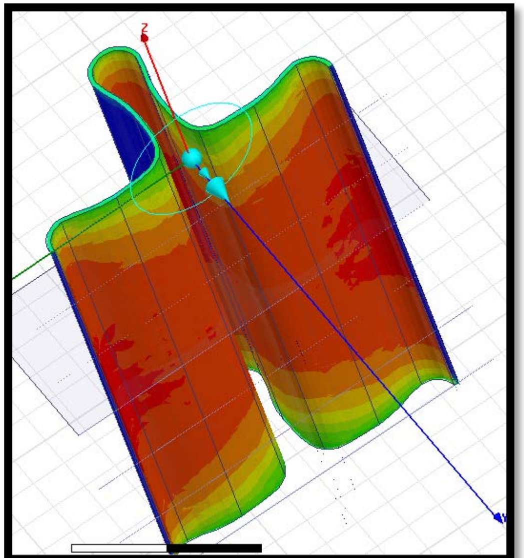


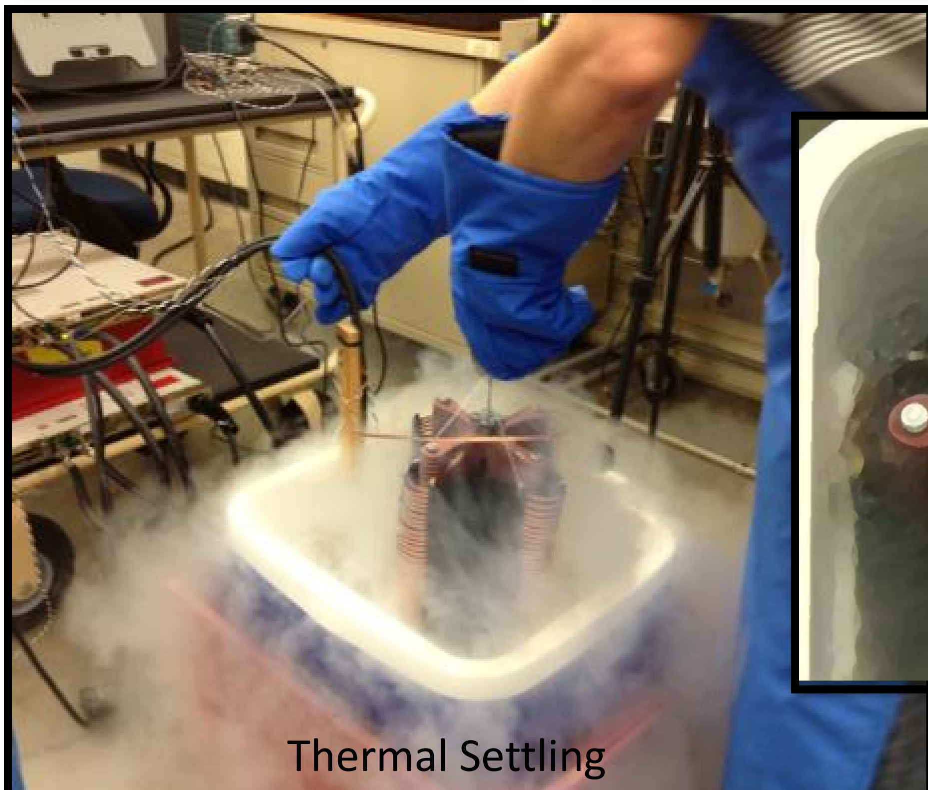
Coil Fully Collapsed

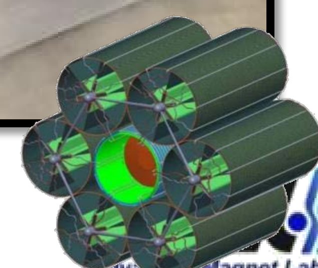
Inserting into Helium Cryostat

YBCO Test (JSC)

Coil Expansion Test (JSC)





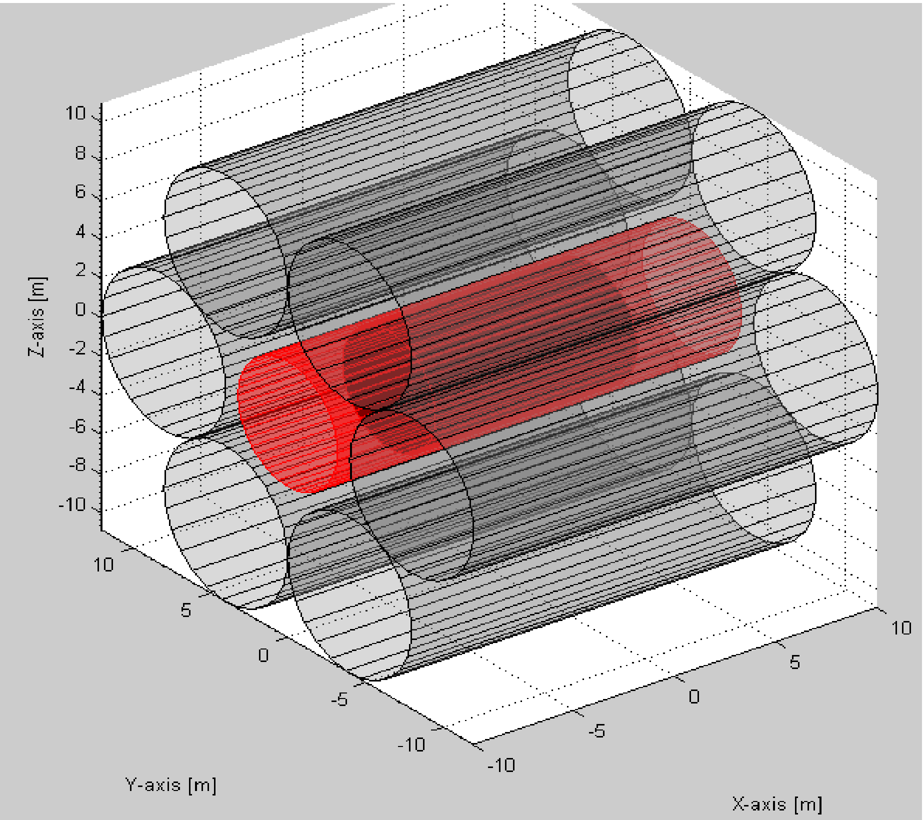


Quench Highlights

Stored Energy

6+1 coil array system to protect the crew from solar and galactic radiation.

Volume per Coil:	~ 1000 m^3
Nominal Current:	~ 40 kA
Stored Energy:	~ 400 MJ
Inductance:	~ 0.4 H



Stored Energy sufficient to melt
570 kg Cu starting at 50 K

Quench -- Operational Issue of Superconductors

What causes a Quench?

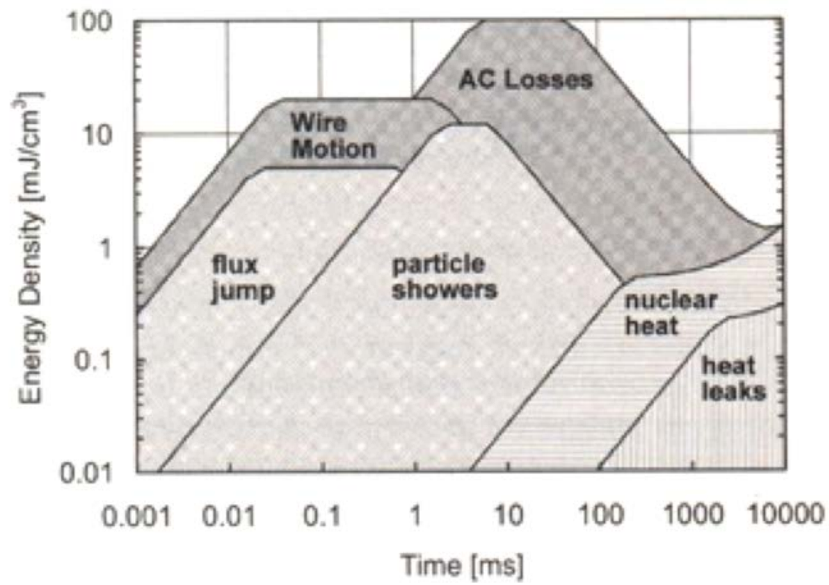


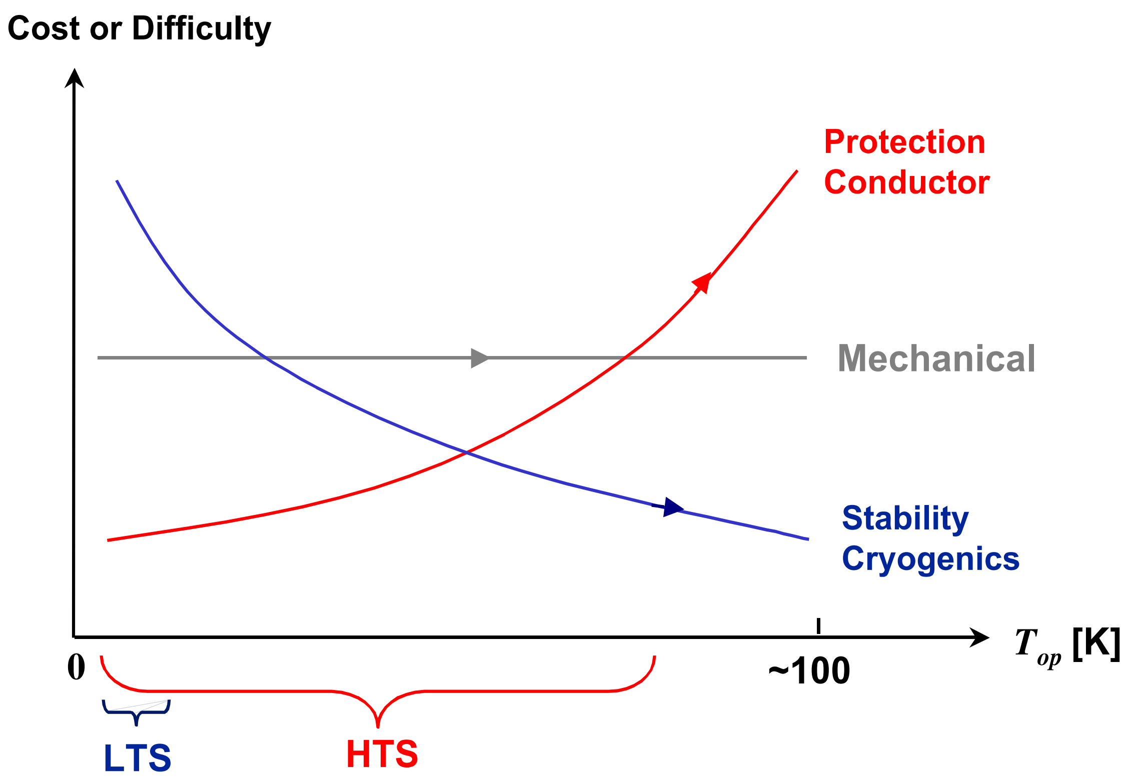
Figure 1: Disturbance energy spectrum acting in superconducting devices presented as energy density in mJ/cm³ versus time duration of the acting disturbance. Stability and Protection of SC Magnets – A Discussion", Y. Iwasa, IEEE Transactions on Applied Superconductivity, p. 1615, June 2005.

Quenching of Superconducting Coils

Quench Protection

2 2

HTS Quench Protection Issues



(. Iwasa (05/08/03)

Advanced Magnet Lab

Summary

- Quench protection of large LTS magnets standard technique using passive and active methods
- Active quench protection requires reliable quench detection which constitutes potential risk itself
- Quench detection in HTS conductors is *unsolved* due to extremely low quench propagation velocity
- Conductor margin *for mission critical* shielding coils needs to be very large (e.g., MRI coils never quench)
- Expandable shielding coils require high heat conductivity of coil support fabric.
- Graphene-like material might be required

We don't have a solution yet → NIAC

Acknowledgements:

A lot of the presented information on quench has been borrowed from publications of the following people:

- P. Ferracin
- Y. Iwasa
- C.E. Oberly
- S. Prestmon
- J. Schwartz

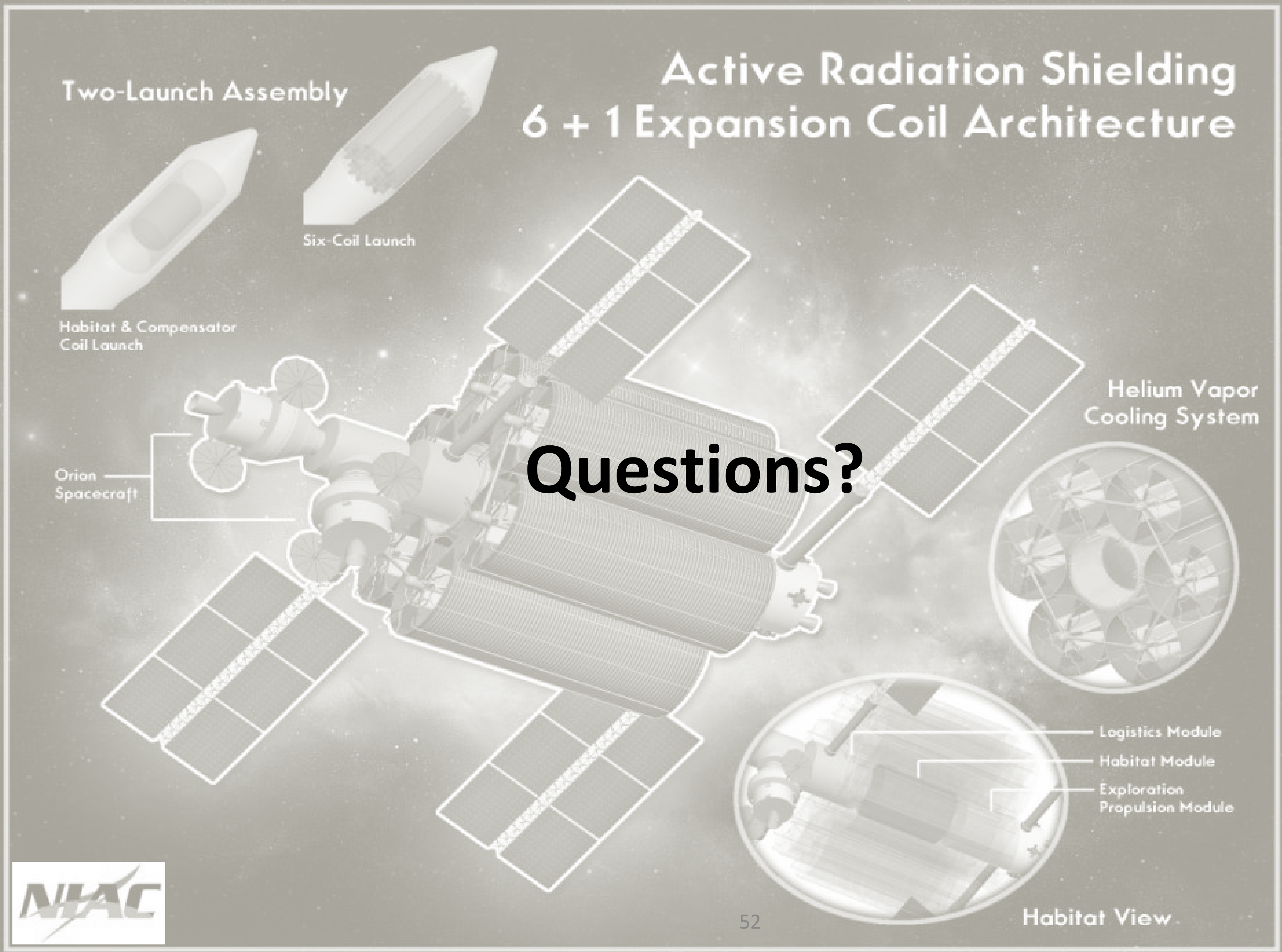
Phase 2 Goals (Remaining)

- The remaining tasks, as planned, include:
  - Failure Scenarios / Quench Protection
  - Shielding Optimization
  - Continued Dose Reduction Performance Analysis (Fringe Field, Habitat mass, GEANT4)
  - Finalize Technology Roadmap, Cost Analysis
  - Coil Expansion Test
  - Final Reporting

Considerations

- How to better manage end cap dose?
  - Fringe field MC analysis
  - Multiple LH_2 propellant tanks instead of 1 tank?
  - Expandable habitat benefit?
  - Can solar arrays play a part in thermal management?
  - Can shielding coils be used as energy storage?

Questions?


Active Radiation Shielding
6 + 1 Expansion Coil Architecture
Two-Launch Assembly
Six-Coil Launch
Habitat & Compensator Coil Launch
Orion Spacecraft
Helium Vapor Cooling System
Logistics Module
Habitat Module
Exploration Propulsion Module
Habitat View

Backup

Environments

- Publications on static magnetic field environments and its bio-effects were reviewed. Short-term exposure information is available suggesting long term exposure may be okay. Further research likely needed.
- Magnetic field safety requirements exist for controlled work environments. The following effects have been noted with little noted adverse effects
  - Magnetohydrodynamic (MHD) effects on ionized fluids (e.g. blood) creating an aortic voltage change
  - MHD interaction elevates blood pressure (BP)
    - 5 Tesla equates to 5% BP elevation
  - Prosthetic devises and pacemakers are an issue (access limit of 5 gauss).
    - Earth field ~0.5 gauss

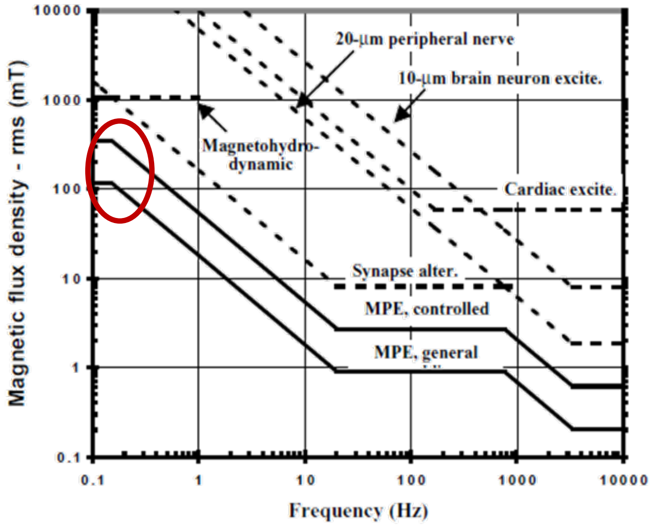


Figure 1— Median thresholds for adverse stimulation from magnetic field exposure (broken lines) and recommended maximum permissible exposure limits (solid lines); whole-body exposure to spatially constant field

Ref.:

1. IEEE C95.6 Safety Standard (2002, revisit 2007)
2. G. Miller, Exposure Guidelines for Magnetic Fields (1987)

Thermal System

- Requires flexible low pressure helium gas circulation loop development for an expandable coil system
- A solar shield was considered in lieu of the helium vapor cooling system however, such a solar shield would not get the coils down to the desired temperature of 40 – 60K
- Power required
  - Cryocoolers will need 600 W at COP 32 W/W and 1.25 contingency for a total of 24kW
    - includes 380 W for compensation coil
    - Cools to 40 K, coolant loop picks up 10W with a 2 K temperature rise in the circuit for a pressure drop of ~200 Pa.

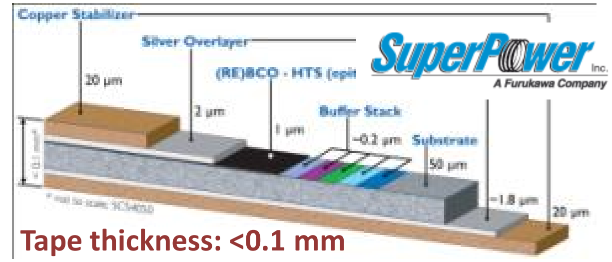
*COP – Coefficient of Performance

State of the Art High Temperature Superconductor (HTS)

- Low Temperature Superconducting
  - Typical Operation: <5K - Boiling point of liquid Helium
    - Most prevalent use is with MRI medical machines
- High Temperature Superconducting
  - Typical Operation: ≤ 77K - Boiling point of liquid Nitrogen
    - HTS, such as YBCO, is not sensitive to conductor movement such as the supersensitive LTS
    - HTS can operate in deep space environment
    - A tape conductor is needed for solenoid coils such as the magnet systems presented here.

YBCO

Yttrium Barium Copper Oxide



Tape thickness: <0.1 mm

Tape thickness: 0.21- 0.23 mm